SCHOOL OF CIVIL ENGINEERING

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-81/7

FRAMEWORK FOR A PAVEMENT EVALUATION SYSTEM

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PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

Interim Report

FRAMEWORK FOR A PAVEMENT EVALUATION SYSTEM

TO: H. L. Michael, Director
Joint Highway Research Project

May 13, 1981

Project: C-36-63G

FROM: E. J. Yoder, Research Engineer
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File: 9-7-7

The attached Interim Report is submitted on the JHRP Research Study entitled "Development of a System for the Evaluation of Pavements in Indiana". The report has been authored by Mr. Sayed Metwali under the direction of Professor E. J. Yoder.

The research covered in this report is a continuation of that reported in the first Interim Report by Mr. Satish Mohan. The research is a cooperative venture of the Indiana State Highway Commission Research and Training Center. Personnel from the Research and Training Center cooperated in laying out the research and they provided the testing equipment and personnel for the field measurements.

The report summarizes data obtained from four pavement types (1) flexible, (2) overlay, (3) joint concrete and (4) continuously reinforced concrete pavements.

In the continuation of the research reported herein, two main experiments were designed to collect and analyze data from in-service pavements in Indiana. The first experiment was aimed at examining the seasonal changes in pavement properties. These properties included pavement deflection, roughness, and skid resistance on each of the four pavement types. This phase also included an investigation into the expected service life of a designed asphalt overlay as a function of the error in estimating the representative deflection at different levels of traffic volumes.

The second experiment was concerned with examining the variability of pavement properties along highway contract sections. After consultation with representatives of the ISHC, it was determined that the contract section as used by the Indiana State Highway Commission should form the basis for the measurements in a pavement management system. Primary effort was concentrated on determining the number of tests required on a contract section to define this representative section of pavement for analysis.

The report includes recommendations for number, location and type of measurements that should be made in a pavement management system. The framework for a potential management system is presented in the report.

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This report is issued as partial fulfillment of the objectives of the study and will be submitted to ISHC and FHWA for review and similar acceptance.

Respectfully submitted,

Eldon J. Yoder

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Interim Report

FRAMEWORK FOR A PAVEMENT EVALUATION SYSTEM

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Project No.: C-36-63G

File No.: 9-7-7

Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana State Highway Commission

and the

U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Purdue University
West Lafayette, Indiana
May 13, 1981

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JHRP-81/7		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
FRAMEWORK FOR A PAVEMENT EVALUATION SYSTEM	May 13, 1981
7. Author(s)	8. Performing Organization Report No.
El-Sayed Wafa Metwali	JHRP-81-7
9. Performing Organization Name and Address	10. Work Unit No.
Joint Highway Research Project Civil Engineering Building Purdue University West Lafayette, Indiana 47907	11. Contract or Grant No. HPR-1(18), Part II
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Indiana State Highway Commission State Office Building 100 North Senate Avenue Indianapolis, Indiana 46204	Interim Report 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration. From research study titled "Development of a System for the Evaluation of Pavements in Indiana".

16. Abstract

The Indiana State Highway Commission is presently setting up a pavement management system which can be used for planning maintenance of the existing highway system. This research was set up to develop procedures and techniques for conducting pavement condition surveys (using the Roadmeter, Dynaflect and Skid Tester) to collect pavement condition information needed as input to the pavement management system.

In-service pavements including flexible, overlay, jointed reinforced concrete and continuously reinforced concrete pavements were evaluated. The primary pavement unit used in this research is the contract section of the ISHC. Two primary experiments were designed and evaluated. The first dealt with examining the seasonal changes in pavement properties. This included deflection data, roughness and skid resistance. Regression correlations were developed for predicting maximum deflection of asphalt pavements from summer and fall measurements. An investigation was made to examine the change in expected service life of the designed asphalt overlay as a function of the error in estimating representative deflection at different levels of traffic volumes. The second primary experience was concerned with examining variability of pavement properties along the highway contract sections.

Recommendations have been made on the number of tests to be made, location of tests and time of testing. This information can be used by the state as input data in their potential management system.

17. Key Words	18. Distribution Statement
Present Serviceability Index, Present Serviceability Rating, Roadmeter, Deflection Measurements, Pavement Evaluation, Pavement Management System	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	231	

Form DOT F 1700.7 (8-69)

ACKNOWLEDGMENTS

The author expresses his sincere appreciation to Professor Eldon J. Yoder, his major professor, for the counsel and guidance during the course of this research and for the thorough review of the manuscript.

With a sense of gratitude and deep respect the author sincerely thanks Professor Harold L. Michael for his constant encouragement, timely advice when needed and for reviewing the manuscript.

Special thanks are due to Professor William H. Goetz for his guidance in the area of bituminous materials and for reviewing the manuscript.

The author is indebted to Professor Virgil L. Anderson who generously gave of his time in assisting with the design of the experimental work and data analysis and for reviewing the manuscript.

The financial support of this research from the Joint Highway Research Project of Purdue University, in cooperation with the Indiana State Highway Commission, is duly acknowledged.

Sincere thanks and appreciation are extended to Mr. Paul Owens, Director, and Mr. Barry Elkin, Assistant Director, Research and Training Center, ISHC, for their high cooperation during the various phases of the research and for providing the equipment and manpower to make the field measurements.

Mr. Joseph Sudol, Research Coordinator, Research and Training Center, is highly acknowledged for his efforts in coordinating the several phases of the field measurements. Thanks are also due to Messrs. S. Gulen, K. Kercher, B. Meyers, B. Balensiefer, Jr. and H. Fincher of the Research and Training Center for their cooperation in the data collection phases.

The author is grateful to Mr. Terrance Dailey, Statistical Consultant, for the many hours spent on discussing the experimental work of this research.

Finally, appreciation is due to Mrs. Marian Sipes for the diligent typing of the manuscript.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

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LIST OF SYMBOLS

AASHO	American Association of State Highway Officials
ANOVA	Analysis of Variance
BCI	Base Curvature Index = S_4-S_5
CRC	Continuously Reinforced Concrete Pavement
DMD	Dynaflect Maximum Deflection
DTN	Design Traffic Number
ISHC	Indiana State Highway Commission
JRC	Jointed Reinforced Concrete Pavement
Mil	Milli-inch (.001 inch)
PMS	Pavement Management Systems
PSI	Present Serviceability Index
R & TC	Research and Training Center
SCI	Surface Curvature Index = S_1-S_2
SN	Skid Number
S_1	Reading of Sensor 1 of the Dynaflect
S_2	Reading of Sensor 2 of the Dynaflect
S_3	Reading of Sensor 3 of the Dynaflect
S_4	Reading of Sensor 4 of the Dynaflect
S_5	Reading of Sensor 5 of the Dynaflect
SPD	Spreadability Parameter = $\frac{(S_1+S_2+S_3+S_4+S_5)}{5\ S_1} \times 100$
TSI	Terminal Serviceability Index

HIGHLIGHT SUMMARY

Pavements represent a major portion of the huge national investment in highway networks. In order to optimally manage the national investment in pavements and keep track of their status and performance, many state highway departments are developing Pavement Management Systems, PMS.

Pavement Condition evaluation is a vital component of any pavement management system. Evaluation is the main source of information for determining the status and rehabilitation needs of the pavement sections within the highway network.

The objective of this research study was to develop procedures and techniques for conducting pavement condition surveys (using the Roadmeter, Dynaflect and skid tester) to collect pavement condition information needed as input to a statewide comprehensive pavement evaluation system.

To achieve the objective of the study, two main experiments were designed to collect and analyze data from in-service pavements in Indiana. Each of the two experiments included the four primary pavement types -- asphalt, overlay, jointed concrete and continuously reinforced concrete pavements. Both experiments were concerned with examining the three pavement properties involved in the evaluation

process: serviceability, structural adequacy and skid resistance as measured by the Roadmeter, Dynaflect and skid tester, respectively.

The first experiment aimed at examining the seasonal changes in pavement properties. Deflection data collected on a seasonal basis showed that seasonal changes have appreciable effects on the deflections of asphalt, overlay and jointed concrete pavements. Regression correlations were developed for predicting maximum spring deflection of asphalt pavements from summer and fall measurements.

The analysis of roughness data showed that the seasonal effects on the measured roughness were minor for all the four pavement types included in the study. Simple and easy-to-use PSI models were developed for predicting the panel rating of pavement serviceability from Roadmeter roughness measurements.

Significant differences were found between the fall and spring skid numbers with the spring values being higher for both asphalt and concrete surfaces.

An investigation was made to examine the change in the expected service life of the designed asphalt overlay as a function of the error in estimating the representative deflection at different levels of traffic volumes.

The second experiment was concerned with examining the variability of pavement properties along highway contract sections. Deflection variability studies indicated that pavement deflections vary significantly from location to location within the same contract. Therefore, for the soil conditions included in this study, and for the length of contract sections in Indiana it was determined that Dynaflect tests should cover the entire length of the contract under evaluation. Recommendations were made relative to the optimal Dynaflect testing intensity on each pavement type.

The roughness data showed that one pass of the Roadmeter would provide an accurate roughness indication. It was also found that roughness variation between the two lanes on two-lane highways was generally nonsignificant.

Skid variability studies indicated that the friction measurements must cover the entire length of the contract being evaluated. Based on the estimated components of skid resistance variability; correlations were developed between the testing intensity and the accuracy of the measurements.

Finally, a discussion of the framework of a comprehensive evaluation system and its interrelated activities involved in the evaluation process is presented.

CHAPTER 1

INTRODUCTION

General Background

It is a well known fact that highway networks represent a major national investment in transportation. The pavement portion of this investment is, in turn, quite substantial. Statistics show that pavements are the largest single element of cost in highways representing 30-40% of highway capital expenditures (11)*. The FHWA estimates that about \$60-80 billion has been spent on all classes of U.S. pavements since the Highway Trust Fund was created in 1956 (11). In addition, sections on the Interstate highway system that have exceeded their design life and are now worn out will cost \$2.3 billion to replace. Over the next 20 years, rehabilitation on this national network will cost \$21.7 billion in 1979 dollars (60).

The nation's aging highway system, high traffic volumes, increased truck weights and the competition for the tax dollar have combined to make the work of the transportation administrator ever more difficult. Highway departments are short of dollars and managers are called upon to "make one dollar do the work of two". This is not easy. Therefore, efficient systems are needed to provide systematic and objective information to establish rehabilitation priorities among candidate sections in a roadway network.

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*Numbers in parentheses refer to the references listed at the end of this report.

This has resulted in the development and implementation, by several states across the nation, of what became known as Pavement Management Systems, PMS (6,15,23,27,33,37,47,48,50,57). In a broad sense, pavement management systems are concerned with the entire spectrum of interrelated activities involved in the process of providing pavement systems. These range from the planning phases through to design, construction, maintenance and in-service evaluation (27). The management systems enable the transportation administrator to make objective assessments in developing his programs and financing needs.

Essentially, a good pavement evaluation system is the cornerstone of a good pavement management system. Decision makers are always faced with questions relative to the status and performance of various pavement sections within highway networks. To optimally spend their maintenance dollars highway managers need specific information relative to where the deficient sections are and the required improvements. The pavement evaluation system provides the primary source of information for use at all levels and in all activity areas of a pavement management system. Pavements can be objectively evaluated by measuring their properties to provide input to managerial decision making.

Components of a Comprehensive Pavement Evaluation System

A comprehensive pavement evaluation system essentially consists of four main components; these are

(1) Pavement properties - that can be objectively measured and used to evaluate pavement condition. Three properties have been identified as indicators of pavement condition and performance with time -- serviceability, structural adequacy

and skid resistance. Serviceability is a measure of the riding quality as viewed by the average highway user. Structural adequacy is concerned with the ability of the pavement system to withstand the effects of traffic loads during its anticipated life without losing its integrity. Skid resistance is a measure of pavement friction which relates to the ability of pavement to provide safe traffic operations under wet conditions.

(2) Reliable and efficient equipment - capable of accurately measuring the pavement properties discussed above. Several measuring equipment are available for conducting field measurements of pavement properties. Pavement roughness has been identified as a primary indicator of serviceability. Roughness measurements can be made using a variety of devices such as Bureau of Public Roads Roughometer (BPR), CHLOE Profilometer, Surface Dynamics Profilometer and Car Roadmeters (Mays and PCA) (66). The Roadmeters are by far the most popular roughness measuring equipment due to their speed and ease of operation. A detailed discussion on the PCA Roadmeter is given in Chapter 2. Nondestructive structural evaluation is performed by measuring pavement response to load as indicated by surface deflections. A number of instruments have been used to measure surface deflection (26). These include the Benkelman Beam, Travelling Deflectometer, Dynaflect and Road Raters. The Dynaflect is widely used by several states including Indiana.

A detailed description of the Dynaflect is given in Chapter 6. Pavement skid resistance is usually measured in the field by the trailer-type equipment such as the locked-wheel skid tester which measures pavement friction as the force required to drag a non-rotating tire over a wet pavement and the Mumeter which evaluates the side friction factor (56). Other methods for measuring skid resistance have been used, but not on a large scale, such as the pendulum type device and recent techniques employing stereophotographs for analyzing surface texture and then infering about its skid resistance from correlations with other measuring equipment (56). The locked-wheel skid tester is discussed in more detail in Chapter 4.

(3) Systematic procedures - for using the available equipment to obtain a set of measurements suitable for the most objective pavement condition description possible. It is considered very desirable to have information on as many highways as possible in order to provide the management with a clear picture of the status of the pavement sections within the highway network. An efficient pavement evaluation system, hence, is one that is capable of using available equipment for conducting mass inventories on a network basis within a reasonable period of time and at the same time insures accuracy and economy of the measurements. In addition, consistency of the measurements is considered essential for providing comparative values for different highway sections.

(4) Efficient feedback data systems - for data collection, storage, retrieval and presentation. These systems are considered essential for providing the management with a concise summary of the field measurements. To be of practical use, the information must be presented to the management in clear and compact forms that provide answers to the following questions:

(i) Where are the deficient sections in need of rehabilitation?

(ii) What type of an improvement is required?

(iii) What is the amount of the required improvement?

The answers to these questions are needed to objectively identify highway pavements' needs and provide fiscal programming data. In addition, access to detailed and specific information on any section's design, construction, maintenance, age performance (from previous measurements) and traffic conditions must be readily available. This can be achieved through modern electronic computers capable of data editing, storage, updating and retrieval.

Background of the Research Study

The research study was initiated in 1977 with the ultimate goal of establishing a methodology for describing pavement condition in terms of objective measurements using the equipment possessed by ISHC Research and Training Center. The equipment involved included the Roadmeter, Dynaflect and skid tester. An interim report was prepared in October 1978 (42). The following is a brief summary of the approach that was taken and the results of the analysis given in the interim report.

(1) Scope of the study. A study area having a 70-mile radius was delineated around Lafayette. This was done in order to facilitate testing operations and at the same time obtain a suitable inference space for the statistical analysis. It was decided to include four types of pavement in the study. These are: asphalt, overlay, jointed reinforced concrete (JRC) and continuously reinforced concrete (CRC) pavements.

(2) Selection of test sections. A total of 94 test sections, each 1 kilometer long, were selected, totally at random, within the study area for serviceability studies. The sections were arranged in 5 travel loops for testing operations. Dynaflect and skid tester measurements were made on 46 test sections, each 400 meters in length. These sections were subsections of the 1-kilometer sections mentioned above.

(3) Serviceability studies. A Roadmeter variability study was conducted and standard conditions for Roadmeter operations were established. The Roadmeter output was calibrated against the subjective ratings of a panel of 20 raters and PSI models were developed. Models were also developed for predicting PSI from both Roadmeter output and distress manifestations (cracking, patching and rutting).

(4) Deflection studies. Pavement deflections were measured using the Dynaflect. Three deflection profiles were obtained in the travel lane of each test section: right wheel path, center of lane and left wheel path. The measurements were made in the fall of 1977 and the spring of 1978. It was concluded that deflections measured at the right wheel path are the critical ones that must be used for evaluation and overlay design purposes. Models were developed for predicting spring deflections from fall measurements.

(5) Skid-resistance studies. The locked-wheel skid tester was used for making the skid resistance measurements during the fall of 1977 and the spring of 1978. The analysis indicated that nonsignificant difference was found between the two seasons.*

(6) Recommendations. Recommendations were made relative to a general framework for a pavement evaluation system.

Study Purpose

Evaluation is the primary source of information for determining the needs of the roadways within the highway agency's preview as well as setting rehabilitation priorities and planning fiscal programs. A pavement evaluation system is concerned with collecting specific data on certain pavement properties by performing a set of measurements utilizing reliable equipment. A comprehensive and effective evaluation system involves the determination and continuous monitoring of the condition of the highway pavements within a given network. To be of practical use, however, the system must be capable of conducting mass

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*Seasonal effects were found significant during the 1979-1980 period (see Chapter 4).

inventories within a reasonable period of time as well as providing data of acceptable accuracy at a reasonable cost. Consequently, efficiency and accuracy become highly desirable system characteristics.

Although the information provided by the evaluation system is used to make decisions on the network level. The evaluation process itself, however, is carried out in the field on individual pavement segments. This field work is clearly a project-level activity. Therefore, a need existed to develop guidelines for conducting evaluation surveys on pavement sections to assess their condition in terms of objective measurements.

It was the ultimate goal of this research to develop procedures and techniques for conducting pavement condition surveys (using the Roadmeter, Dynaflect and skid tester) to collect pavement condition information needed as input to a statewide comprehensive pavement evaluation system.

It has been realized that for an ultimate evaluation system the highway network must be divided into smaller and manageable sections. These sections should be relatively homogeneous over their length with respect to age, design, materials, construction and traffic conditions. Most of the time construction contracts cover these factors. In other words, a pavement belonging to a given contract is expected to have a certain design (structurally speaking), specific soil conditions, material properties, construction techniques and traffic conditions. Exact techniques, however, relative to how to perform condition measurements on highway sections of considerable lengths (i.e. contract sections) were needed. A primary objective of this research was to develop such techniques.

It was also realized that for a continuous and comprehensive evaluation system, pavement condition measurements will have to be made during different times of the year under different seasonal conditions. Therefore, in order to provide comparable values for pavement properties measured on different highway sections of different conditions and characteristics; it was considered necessary to study and evaluate the effects of the seasonal changes on the measured pavement properties involved in condition evaluation. This was another major objective of the research study.

Study Design and Scope

At the outset, it was recognized that for establishing optimal procedures for conducting comprehensive condition surveys two kinds of variations in the measured pavement properties (roughness, deflections and skid resistance) needed to be examined in some detail; these are

(1) The variability of pavement properties along highway sections of considerable lengths (contract sections)

(2) The seasonal variations in the measured properties.

Developing an understanding of the nature of these two variabilities was considered a prerequisite for establishing a consistent methodology for making the measurements.

To carry out the intended objectives of this study it was necessary to set out a specific framework for the statistical analysis and the data collection programs. Consequently, two main statistical experiments were designed. The first experiment was concerned with evaluating the seasonal variations in pavement properties. The second was directed towards studying the variability of pavement properties along contract sections.

As mentioned earlier, four pavement types were considered in this research (1) asphalt, (2) overlay, (3) JRC and (4) CRC pavements. However, realizing that there are inherent differences between these pavement types; it was decided to evaluate each pavement type separately in order to get a clear view of its behavior.

According to the experimental designs for the statistical analysis, two main field data collection programs were followed in this research (1) seasonal testing and (2) contract variability testing. During each program data were collected from in-service test sections belonging to the 4 pavement types. For each pavement type, three properties were measured (1) roughness, (2) deflections and (3) skid resistance. The Roadmeter, Dynaflect and skid tester, operated by personnel from ISHC Research and Training Center, were used for making the field measurements.

The seasonal testing program consisted of making tests on a seasonal basis (fall and spring) on the same test sections that were tested in 1977 and 1978. These sections were of relatively short lengths (1 kilometer for roughness measurements and 400 meters for deflection and skid resistance measurements). The purpose of this testing was to evaluate the seasonal changes in pavement properties.

The variability testing involved randomly selecting three contract sections for each pavement type, then randomly selecting three 1-mile locations within each contract for studying the variability of pavement properties in order to reach at the accuracy associated with any given testing intensity. All testing operations related to variability studies were made during the summer of 1980 using the Roadmeter, Dynaflect and skid tester.

Pavement Evaluation in Other State Highway Departments - An Overview

The emphasis in the literature review related to this research was directed towards looking into the practices followed by other states, especially the leading ones in PMS, for evaluating their highway pavements. The following represents a brief summary of these practices.

Utah

The PCA Roadmeter is used for making roughness measurements on 1-mile increments within each contract. The results are used to predict average PSI for the contract. The Mumeter is used to make skid tests on a 1/4-mile section every two miles. Additional tests may be made for slippery areas. Computer listings are generated for roughness and skid showing the relative condition of the different sections. Sections selected for rehabilitation are tested with the Dynaflect at one location per mile. The results are used for determining service life and designing the required overlay thickness.

A computer program that uses an overall priority ranking generates listings of highway sections ranked according to a final condition index (47,48,49).

Washington

A pavement condition rating is estimated for any section using an equation which combines the PCA Roadmeter output as a measure of ride quality (Ride-Score) as well as a distress score based on a subjective rating of the extent of pavement distress within a 200-feet sampled segment from each mile (Distress Score). The equation takes the form:

$$\text{Pavement Condition Rating PCR} = \text{Distress Score} \times \sqrt{1 - \text{Ride Score}/10}$$

Skid measurements are made at 1-mile intervals. Skid values are used as safety criteria only and are not employed in the rating of the pavement. A computer program is employed for evaluating alternative rehabilitation strategies. Each strategy is considered as a sequence of overlays defined by time and thickness in order to keep pavement in a serviceable range. Regression equations are used to predict pavement performance with time for purposes of the evaluation process. The costs involved in the evaluation of rehabilitation strategies include those of the routine maintenance, overlays, highway users, traffic interruption and salvage value of the pavement at the end of the analysis period (33).

Arizona

Dynaflect measurements are made at three locations per mile for inventory purposes. Roughness measurements are made with a Mays Meter to predict a Rideability Index based on a panel rating. Then the ride, deflection and cracking values are used to predict PSI from a regression model. The Mumeter is used for skid resistance measurements for a 500-feet section in each mile for inventory purposes. A computer program is employed to evaluate alternative maintenance strategies using maintenance and user costs as well as pavement condition as criteria for evaluation (64).

California

Use is made of PCA Roadmeter as well as a subjective rating of the severity and extent of defects in order to determine alternative repair strategies for any given section. The dominant strategy which would correct all defects is selected. Deflections are used for overlay thickness design. A test section normally varies from 800 to 1000 feet in length and represents a center mile of roadway. The Travelling Deflectometer takes readings at 25-foot intervals. For the Dynaflect maximum values are obtained every 0.01 mile in the outer wheel track of the sampled section. The friction measurements are made with skid trailers (9,26).

Texas

Structural defects are measured objectively based on a subjective rating. The Mays Meter is used for making roughness measurements every 0.2 mile. The skid trailer is employed to conduct skid inventories. Dynaflect measurements are used for evaluating pavement structural adequacy at 1-mile intervals. The data acquired in the monitoring phase are converted via tables and graphs to a utility scale indicating usefulness of the pavement in values ranging from a 0 percent to 100 percent usefulness. A pavement score is then computed by multiplying all scores for the section. The overall pavement score is the rating used to trigger action, while each individual score is used to indicate what type of action is needed (6).

New York

New York employs a specially instrumented Roadmeter for making ride quality measurements. The device puts out a continuous voltage analog of the interaction amplitude of the vehicle response to pavement profile and speed. Special correlations are used to predict PSI values of different sections and used for determining project programming decisions as well as monitoring the time performance characteristics of the highway sections. Skid data are collected with the skid trailer. Inventory testing is performed at 0.4-mile intervals (45).

Florida

CHLOE Profilometer was first used for rating ride quality from regression equations. A Mays Meter was later correlated with the CHLOE Profilometer and used for predicting ride rating, R R.

Distress manifestations (rutting, patching, ... etc.) are objectively rated on a 100-foot section sampled from each mile rated. The resulting distress rating, DR, is used together with ride rating RR to determine a combined pavement basic rating, BR, using the equation

$$BR = \sqrt{RR \times DR}$$

The basic rating BR is weighed for average daily traffic and used as a criterion for determining the need for resurfacing highway sections (70 and below). A cost effectiveness technique is used for setting rehabilitation priorities. AASHO procedures are used for designing overlays (18,19).

Pennsylvania

The Mays Roadmeter is used for making roughness measurements for predicting PSI (from regression equations). Sections falling below a given PSI (i.e. TSI), depending on highway class, are considered candidate for rehabilitation and are scheduled for structural adequacy evaluation which is performed through deflection measurements. The Road Rater takes deflection readings on candidate sections for overlay design purposes.

Skid measurements are made with a special single-wheel skid trailers at a rate of 3 cycles per mile (21,45).

Kentucky

Pavement roughness data, as measured by the Mays Meter, are used for estimating PSI of highway sections. Traffic maps are used for estimating EAL. The trend of roughness and EAL is determined for each section using a regression equation fitted to the previous data of the section. This allows to predict when a section is expected to reach TSI.

Road Rater's deflections are used for designing asphalt overlays. Skid measurements are conducted at a rate of 2 tests per mile (24,45).

CHAPTER 2

PERFORMANCE STUDIES OF PAVEMENT SERVICEABILITY

The serviceability concept is based on subjective evaluation by the road user of the riding quality of a pavement at a given time. The method was developed by Carey and Irick (10) by correlating the mean panel rating of ride quality of 138 test sections with physical measurements of the surface characteristics. The result was termed the Present Serviceability Index (PSI).

Pavement surface roughness is the primary contributor of serviceability. Studies made at the AASHO Road Test (1) showed that about 95 percent of the information about the serviceability of a pavement is contributed by the roughness of its surface profile.

Study Objective

Pavement roughness measurements using the Roadmeter are a very efficient means for screening highway pavements relative to their present serviceability. By setting minimum serviceability standards, the sections falling below these standards can be identified and scheduled for further inspection and possible rehabilitation.

The objective of this portion of the study was to examine seasonal changes in roughness so that recommendations can be made relative to the appropriate timing of making roughness measurements. Another objective was to re-evaluate the correlations between measured roughness and pavement serviceability using data collected by Mohan in the first part of the research study (42).

Study Design

Analysis of the seasonal variations in measured pavement roughness and roughness-serviceability correlations covered the four types of pavements included in this research effort. In the first part of the study (1977-1978) 94 sections each 1 km (0.62 mile) in length were considered for roughness measurements. The sections were arranged into five travel loops for convenience of testing (42). A map of these sections is provided in Appendix A (Figure A1). The geographic locations of these sections are shown in Table A1 in Appendix A.

In this part of the study, 76 sections were included for roughness studies. A summary of the data can be found in Table B1 in Appendix B.

The Roadmeter

Roadmeters have become very popular with highway agencies during the past few years for measuring road roughness (46). The Roadmeter is a simple electromechanical device that measures the number and magnitude of vertical deviations between the body of a car and the center of the rear axle. This is accomplished, as shown in Figure 2.1 with a flexible cable attached to the differential housing. The cable passes over pulleys and is restrained by a spring. A roller-type switchplate, divided into 1/8 inch segments, records the vertical deviations. The resulting counts are displayed in the counter-panels that are usually placed at the front seat between the driver and the recorder as shown in Figure 2.2.

The Roadmeter is capable of operation with a minimum of training and personnel. It is capable of acquiring roughness data on a mass

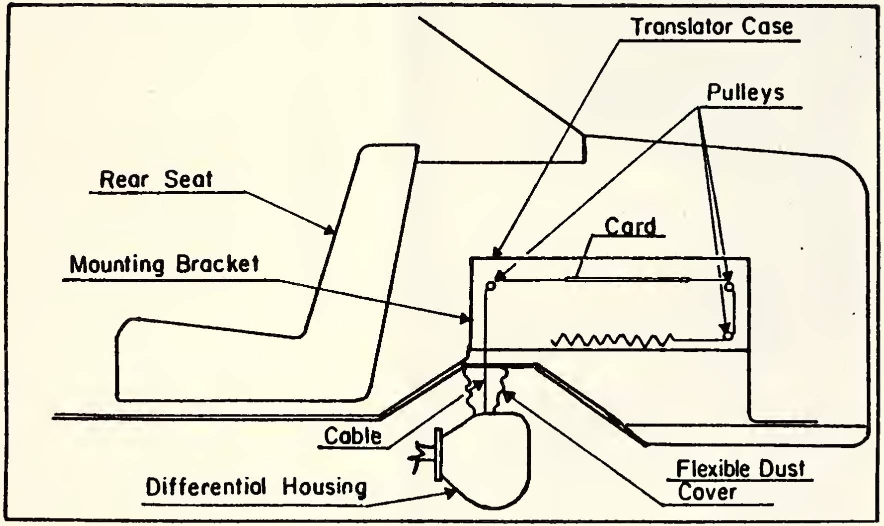

Figure 2.1. Schematic of the Roadmeter (after John Cox and Sons, Inc.)

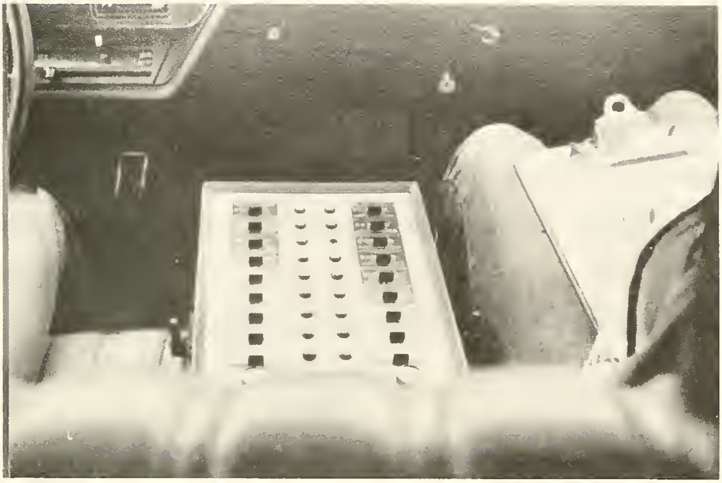

Figure 2.2. The Counter Panel of the Roadmeter

inventory basis. The operation speed is near normal traffic speeds (50 mph), thereby eliminating the need for traffic control. Recording instrumentation is of rugged construction and is capable of continuous operation with a minimum of downtime and with ease of maintenance.

Data Collection

Roughness measurements were made by personnel from ISHC Research and Training Center using the PCA Roadmeter. The measurements were conducted on a seasonal basis (fall and spring) on the same test sections. Three Roadmeter passes were made on each section at each visit.

The fall measurements were made during November and the spring measurements were made during May.

Development of New Present Serviceability Index Models

In the interim report (42) present serviceability index (PSI) models were developed for the previously mentioned four types of pavement. The objective of these models was to use the Roadmeter output (roughness counts per km) in order to predict pavement serviceability from the highway user's point of view.

A pavement serviceability rating panel, consisting of 20 raters, was appointed to make a subjective judgment of the ride quality of 94 pavement sections. The panel's judgment was indicated by a rating value ranging from 0 to 5 with adjective designations of very poor (0-1), poor (1-2), fair (2-3), good (3-4) and very good (4-5). The PCA

Roadmeter owned by the ISHC's Research and Training Center was then used to measure the roughness of these sections. In addition, the amount of cracking, patching and average rut depth were measured.

Using mathematical analyses, the above quantitative measures were related to the mean rating value as established by the rating panel to produce an equation to predict a quantitative counterpart of the mean rating value. Two PSI models were developed for each pavement type -- a full model and a reduced model. In the full model the distress manifestations (cracking, patching, etc.) were included as well as the Roadmeter counts. In the reduced model only the Roadmeter output was included. The reduced models were intended to be a simplified means for conducting mass serviceability inventories. Table 2.1 shows the reduced PSI models.

In this study, the reduced models were re-evaluated to develop easy-to-use and practical models suitable for a comprehensive statewide evaluation system. It was noticed that the reduced models were in a logarithmic form and that the equations produced curvilinear correlations. Another observation was that multiple Roadmeter passes were used individually with the same mean panel rating rather than using the averaged Roadmeter passes.

Regression analyses on the data provided the new PSI models shown in Table 2.2. Figures 2.3 to 2.5 show the plots of the data and the best fit regression lines. Comparing the new models developed herein (Table 2.2) to the ones in Table 2.1, it can be noticed that the new models have higher correlation coefficients than the previous values.

TABLE 2.1. REDUCED PSI MODELS FROM MOHAN (42).

PAVEMENT	MODEL	R^2
ASPHALT	$PSI = -9.2556 + 10.3244\ (LOG\ C) - 2.048\ (LOG\ C)^2$	0.78
OVERLAY	$PSI = 18.7414 - 9.5708\ (LOG\ C) + 1.423\ (LOG\ C)^2$	0.70
JRC	$PSI = 8.0677 - 1.5387\ (LOG\ C)$	0.57
CRC	$PSI = 4.9354 - 0.1274\ (LOG\ C)^2$	0.46

PSI = PRESENT SERVICEABILITY INDEX
C = ROADMETER COUNTS PER KILOMETER

TABLE 2.2. NEW SIMPLIFIED PSI MODELS.

PAVEMENT	MODEL*	R^2
ASPHALT	$PSI = 3.94 - 0.00072\ C$	0.79
OVERLAY	$PSI = 4.37 - 0.00174\ C$	0.77
JRC	$PSI = 4.69 - 0.00141\ C$	0.88
CRC	$PSI = 4.40 - 0.00070\ C$	0.59
JRC&CRC (COMBINED)	$PSI = 4.58 - 0.00114\ C$	0.71

*The analysis was made on the average counts obtained from the individual passes. The analysis on individual passes gave lower R^2 values.

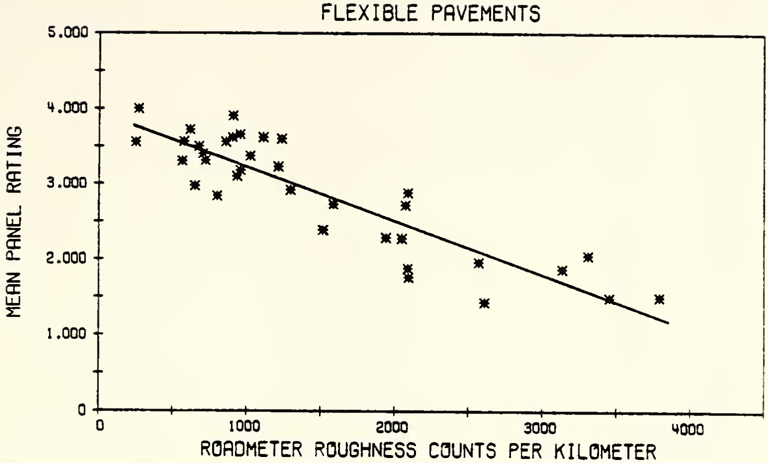

Figure 2.3. Relationship Between Mean Panel Rating and PCA Roadmeter Roughness Counts Per Kilometer (Flexible Pavements)

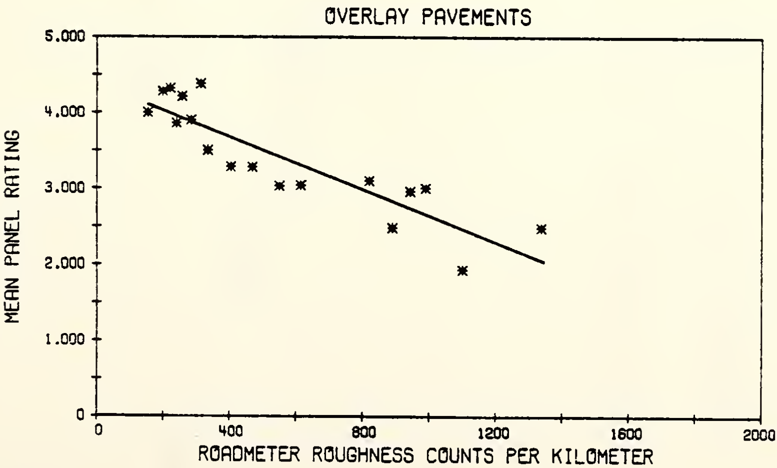

Figure 2.4. Relationship Between Mean Panel Rating and PCA Roadmeter Roughness Counts Per Kilometer (Overlay Pavements)

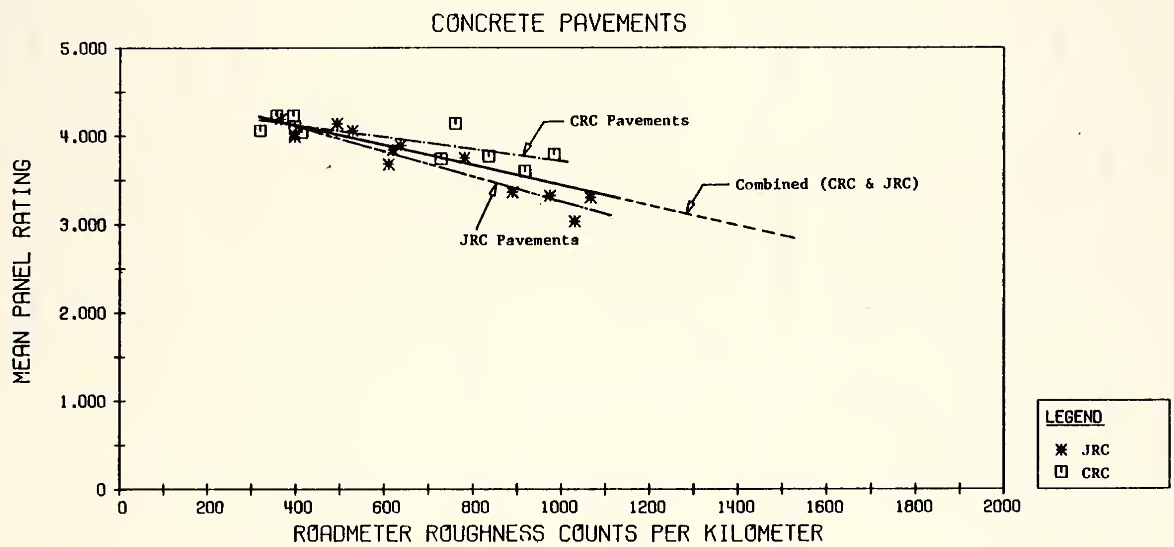

Figure 2.5. Relationship Between Mean Panel Rating and PCA Roadmeter Roughness Counts Per Kilometer (Concrete Pavements)

Although distress manifestations were not included in these models, they provide good accuracy as indicated by the correlation coefficients. The measurement of cracking, patching and rut depth present problems relative to safety and time. Collection of these data require personnel to be on the travelled highway subjected to the dangers of traffic. Traffic control to minimize the dangers are both costly and time consuming. The volume of statewide mileage to be surveyed is large and it is felt that the expenditure of time for traffic control precludes use of physical measurements on a routine basis.

Analysis of Seasonal and Time Variations in Pavement Roughness

Statistical Model

The roughness data collected during the study were analyzed using analysis of variance techniques, ANOVA, (3). The model used in the analysis took the following form:

$$Y_{ijk\ell} = \mu + S_i + \delta_{(i)} + T_j + ST_{ij} + E_k + SE_{ik} + TE_{jk} + STE_{ijk} + \varepsilon_{(ijk)\ell} \qquad (2.1)$$

$$i=1,2,\ldots,n \quad j=1,2 \quad k=1,2 \quad \ell=1,2,3$$

where

$Y_{ijk\ell}$ = Roadmeter counts/km

μ = overall mean

S_i = effect of the ith test section

$\delta_{(i)}$ = restriction error

T_j = effect of the jth time period

E_k = effect of the kth test season

ST_{ij} = interaction of the ith test section with the jth test period

SE_{ik} = interaction of the ith test section with the kth test season

TE_{jk} = interaction of the jth time period and the kth test season

STE_{ijk} = interaction of the ith test section and the jth test period and the kth test season

$\varepsilon_{(ijk)\ell}$ = random error caused by the ℓth pass on the ith section in the kth season of the jth period, $NID(0,\sigma^2)$

n = number of test sections included in the analysis.

Asphalt Pavements

Figure 2.6 shows the general seasonal and time changes in the measured roughness of asphalt test sections. The analysis of variance on the data as summarized in Table 2.3 showed that the effects of seasonal variations on asphalt pavement roughness were non-significant. This means that roughness measurements conducted in the fall do not vary significantly from the measurements made during the spring. This conclusion has an important practical implication in the sense that roughness measurements made at different times of the year will provide a good indication of the present serviceability of the particular section tested and this indication is not expected to experience significant variations from season to season. Figure 2.8 shows the relationship between spring roughness and fall roughness for asphalt sections and as can be noticed, the best fit regression line has almost 45 degrees inclination indicating the closeness of the spring measurements to the fall ones.

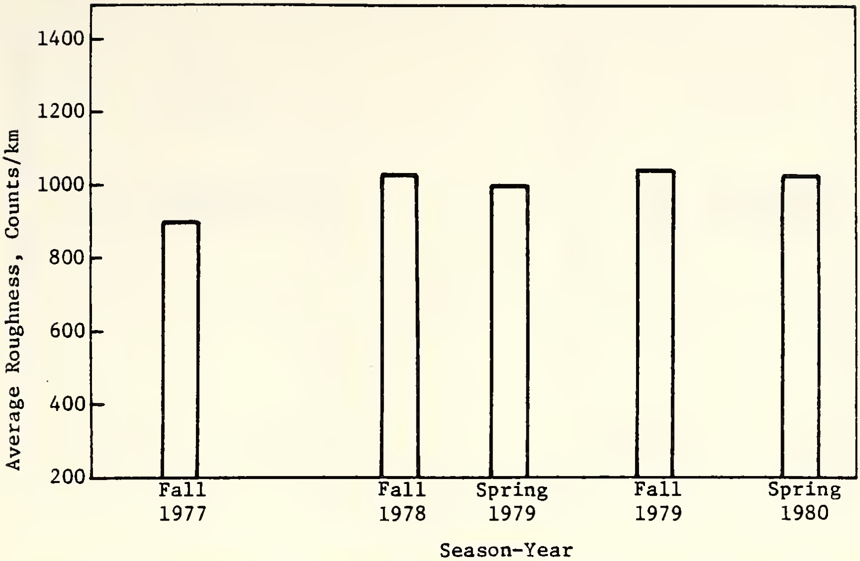

Figure 2.6. Changes in the Average Roughness of 7 Asphalt Test Sections

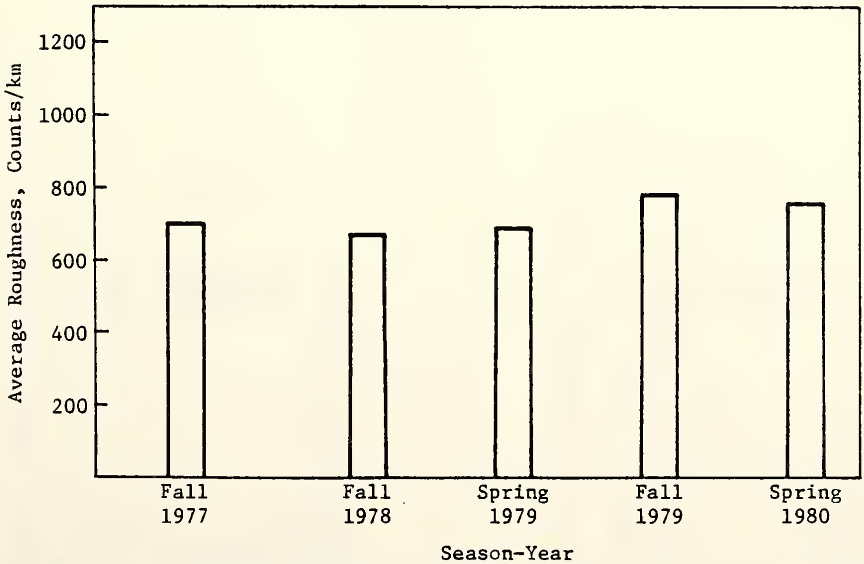

Figure 2.7. Changes in the Average Roughness of 6 Overlay Test Sections

TABLE 2.3. ANOVA- ROUGHNESS, ASPHALT SECTIONS

SOURCE	DF	MS	F
S	6	3430000	
ERROR	0	-------	
T	1	12168	< 1
ST	6	195392	30.3 *
E	1	9793	< 1
SE	6	35525	5.5 *
TE	1	324	< 1
STE	6	32380	
ERROR	56	6443	

* SIGNIF. AT .01
S=SECTION , T=TIME , E=SEASON

TABLE 2.4. ANOVA- ROUGHNESS, OVERLAY SECTIONS

SOURCE	DF	MS	F
S	5	1470000	
ERROR	0	-------	
T	1	24347	1.5
ST	5	16578	15.3 *
E	1	53465	4.7 **
SE	5	11316	10.4 *
TE	1	15138	2.7
STE	5	5527	
ERROR	48	1086	

* SIGNIF. AT .01 **NONSIG. AT .05
S=SECTION , T=TIME , E=SEASON

TABLE 2.5. ANOVA- ROUGHNESS, JRCP SECTIONS

SOURCE	DF	MS	F
S	5	1200000	
ERROR	0	-------	
T	1	642	< 1
ST	5	9526	5.7 *
E	1	245117	9.3 **
SE	5	26507	16.0 *
TE	1	4247	1.8
STE	5	2409	
ERROR	48	1659	

* SIGNIF. AT .01 **NONSIG. AT .04
S=SECTION , T=TIME , E=SEASON

TABLE 2.6. ANOVA- ROUGHNESS, CRCP SECTIONS

SOURCE	DF	MS	F
S	4	1750000	
ERROR	0	-------	
T	1	61568	5.8 *
ST	4	10614	8.0 **
E	1	35527	1.4
SE	4	25136	19.0 **
TE	1	208388	14.3 ***
STE	4	14616	
ERROR	40	1324	

*NONSIG .AT .05 **SIG. AT .01 ***SIG. AT .05
S=SECTION , T=TIME , E=SEASON

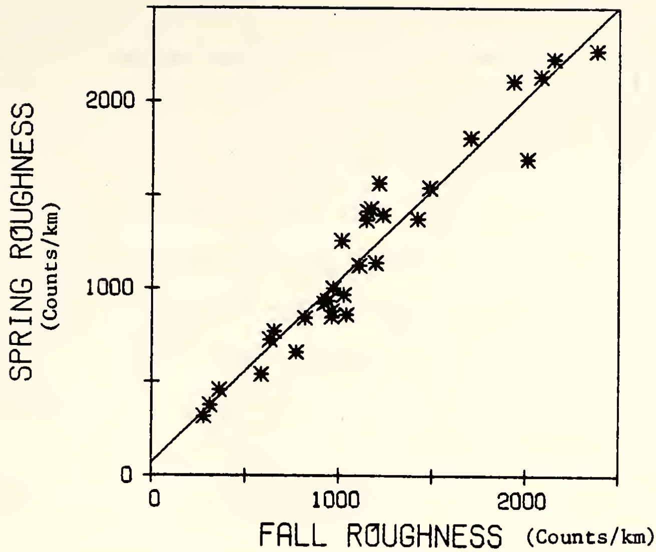

Figure 2.8. Relationship Between Spring and Fall Roughness - Asphalt Test Sections

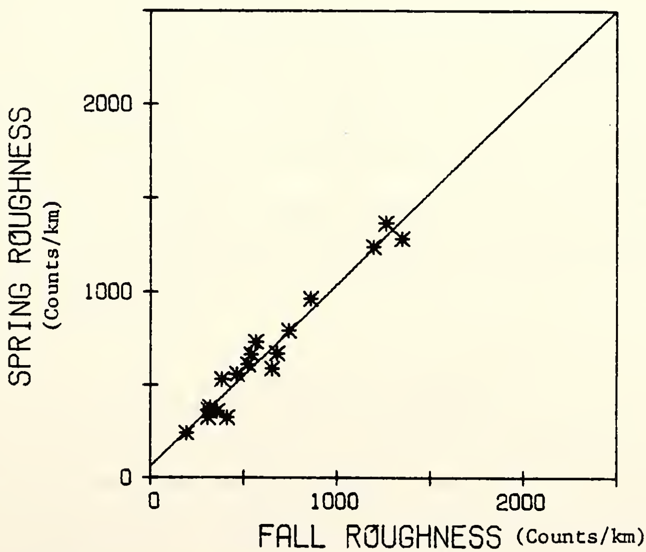

Figure 2.9. Relationship Between Spring and Fall Roughness - Overlay Test Sections

The analysis also showed that there were no significant variations in the measured roughness during the period of the study as shown in Table 2.3 and Figure 2.6. The analysis of variance indicated the significance of section by time interaction which reflects the inherent behavior of individual highway sections. These results provide evidence that the changes in asphalt pavement roughness do not follow a constant rate but, rather, these changes vary from year to year and from section to section. This, in turn, indicates the need to closely monitor the changes in the roughness of individual highway contracts from year to year in order to get an accurate view of the loss of serviceability (increase in roughness) with time.

Overlay Pavements

The results of the analysis of the data collected from overlay pavements are summarized in Table 2.4 as well as Figure 2.7 and Figure 2.9. It was found that seasonal effects caused no significant changes in the measured roughness of overlay pavements. Also, no significant changes were detected for the test sections during the course of the study (fall 1977, 1978, 1979). Again, pronounced variations were detected for individual sections as indicated by a significant section by time interaction term.

Effect of Overlays on Roughness

Figures 2.10 and 2.11 depict the changes in roughness for asphalt and overlay sections that received asphalt overlays. It is obvious that a great reduction in roughness (i.e., gain in serviceability) was achieved from the overlays.

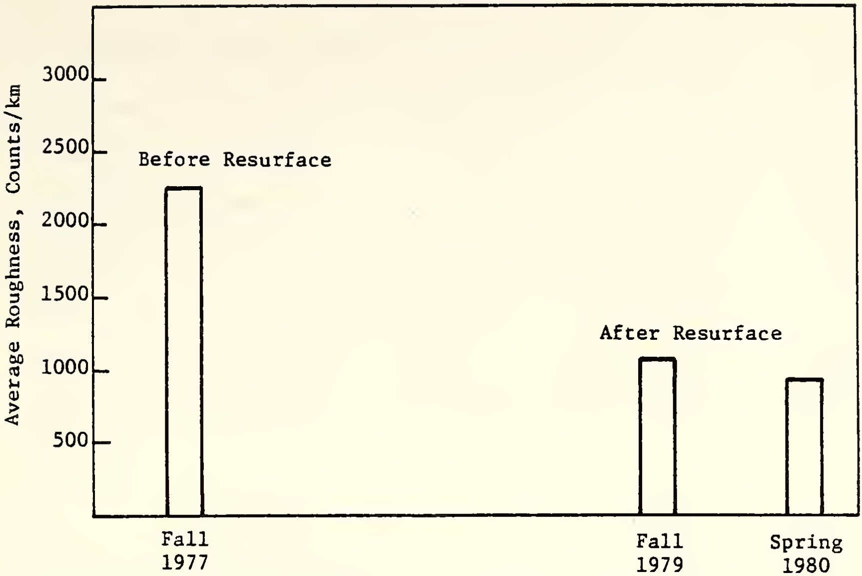

Figure 2.10. Average Roughness of 10 Asphalt Sections Before and After Resurfacing

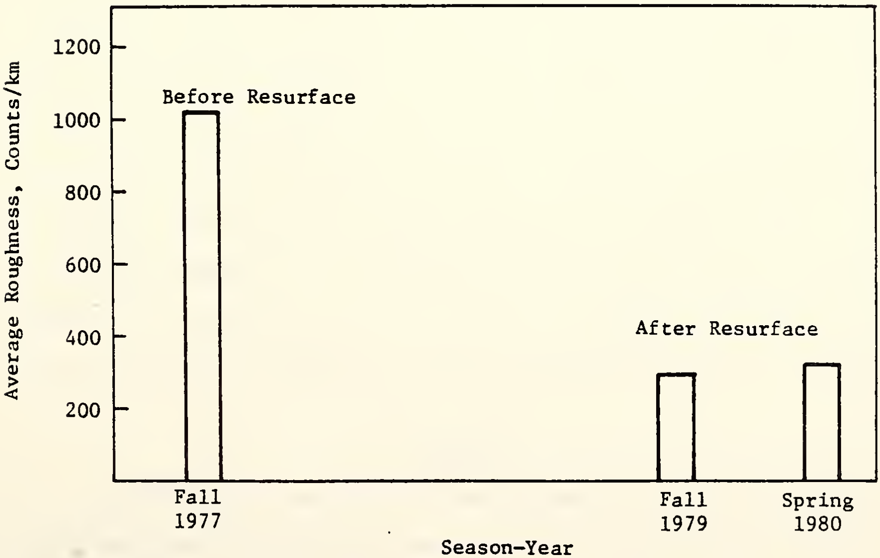

Figure 2.11. Average Roughness of 5 Overlay Test Sections Before and After Applying Additional Resurface

Jointed Concrete Pavements

The JRC pavements exhibited similar behavior to asphalt and overlay pavements relative to the nonsignificance of the seasonal changes in their roughness (Table 2.5 and Figure 2.12). The analysis showed a significant difference in roughness between 1977 and 1978. On the other hand, no appreciable difference was found between 1978 and 1979. Coupled with the fact that the section by time interaction is significant, the same observation is emphasized again relative to the inherent variation in the behavior of individual highway contracts with respect to time.

Continuously Reinforced Concrete Pavements

The analysis of CRC pavement data indicated, as shown in Table 2.6, that these pavements do not undergo appreciable seasonal changes relative to their roughness. The spring-fall relationship is shown in Figure 2.13, and it supports the previously mentioned conclusion drawn from the analysis of variance. When the roughness measured during the fall of 1977 was compared to that measured in the fall of 1978, analysis of variance gave significant difference. A similar comparison between 1978 and 1979 measurements gave nonsignificant roughness changes. The conclusion drawn for the other pavement types applies also to CRC pavements that each section has its own rate of roughness change with time as indicated by a significant section by time interaction in Table 2.6.

Summary

New PSI models, suitable for mass Roadmeter inventories in Indiana, were developed for the four types of pavement included in the research

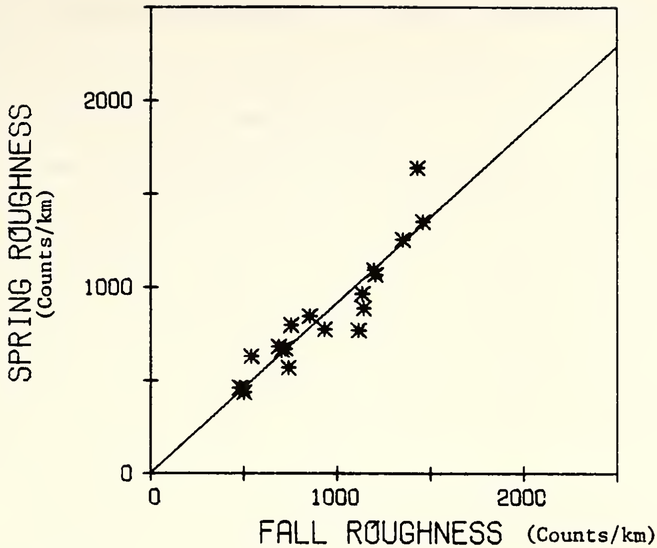

Figure 2.12. Relationship Between Spring and Fall Roughness - JRC Test Sections

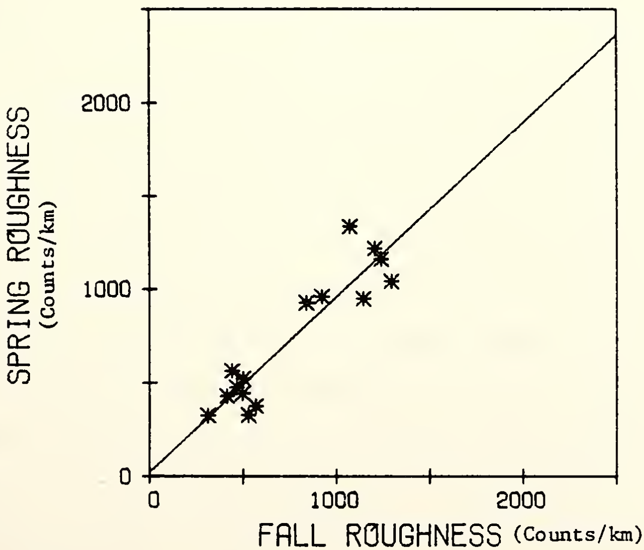

Figure 2.13. Relationship Between Spring and Fall Roughness - CRC Pavement Test Sections

study. These models are based on linear correlations between the Roadmeter output and the mean panel rating. The models are simple and suitable for practical applications.

It was concluded that the seasonal variations in measured roughness are statistically nonsignificant. This conclusion has an important practical aspect in terms of allowing the roughness measurements for serviceability evaluation to be made on a statewide basis during the test season and at the same time providing comparable PSI values for different highway contracts tested during different months (in the same test season).

A reasonable test season for roughness measurements seems to be from late spring to late fall. A reasonable time would appear to be between mid May to late November. Care should be taken not to test pavements until all distress resulting from the spring thaw period is repaired.

The analysis showed that the time changes in pavement roughness are not uniform, i.e., the increase in pavement roughness (loss of serviceability) does not occur at a constant rate with time, but rather, it varies from year to year. The magnitude of the change in roughness with respect to time (performance) will vary from contract to contract depending on many factors such as pavement design, construction quality, material quality, level of maintenance, pavement age and accumulated traffic loads. Consequently, as a part of an overall evaluation system, there is a need to establish history curves (roughness vs. time) for individual highway contracts in order to plan future needs on a realistic basis.

CHAPTER 3

VARIABILITY OF PAVEMENT ROUGHNESS OVER CONTRACT SECTIONS

Study Objective

Roughness is the primary component of serviceability. Roughness relates to the variation in the longitudinal profile of the highway pavement and translates into rideability from the users' viewpoint.

The objective of this phase of the research study was to develop an understanding of the variability of pavement roughness, as measured by the Roadmeter, along ISHC highway contracts in order to recommend the optimal testing procedure for collecting reliable information on any contract at a minimum of time, effort and cost. This would allow accurate screening of as many contracts as possible during the limited testing season and at the same time ensure efficiency of work and optimum useage of available resources. The ISHC contract refers to a section of road (4-6 miles in length) originally designated by the state as a unit for construction and subsequent maintenance. Use of a contract section minimizes materials and construction variability and is perhaps the most uniform unit that exists along a highway section.

Study Design

An experiment was designed for investigating the variability of roughness measurements along contract sections utilizing the Roadmeter. The investigation covered the four pavement types including in the research study. The experiment was designed to provide answers to the following questions:

1. Are there significant variations in pavement roughness along highway contract sections?
2. Are there significant variations in pavement roughness between both sides of two-lane highways?
3. Are there significant variations in the Roadmeter roughness output from repeated passes on the same section?

Selection of Test Contracts

A total of 16 contracts were selected for the roughness variability study. Each pavement type was represented by four contracts. Each contract had three randomly selected one-mile test locations. The geographic locations of these contracts are provided in Appendix C.

Field Data Collection

Roughness measurements were made with the ISHC Research and Training Center's Roadmeter. The testing consisted of making three passes with the Roadmeter on the contract under study. Each pass covered all the three one-mile locations within each contract. Contracts on multi-lane highways were tested in one direction of travel only, whereas contracts on two-lane highways were tested in the two directions of travel.*

All the testing operations related to roughness measurements were made during the month of July of 1980.

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*A data summary is provided in Appendix C.

Data Analysis and Results

Asphalt Pavements

The analysis of variance model used in the statistical analysis of the various factors involved in the experiment took the following form:

$$Y_{ijk\ell} = \mu + C_i + D_{(i)j} + L_{(ij)k} + \delta_{(ijk)} + P_\ell$$

$$+ CP_{i\ell} + DP_{(i)j\ell} + LP_{(ij)k\ell} + \varepsilon_{(ijk\ell)} \qquad (3.1)$$

$$i=1,2,3,4 \quad j=1,2 \quad k=1,2,3 \quad \ell=1,2,3$$

where

$Y_{ijk\ell}$ = Roadmeter output (counts/mile) of the measured roughness from the lth pass on the kth location within the jth direction in the ith contract

μ = overall mean

C_i = effect of the ith contract

$D_{(i)j}$ = effect of the jth direction in the ith contract

$L_{(ij)k}$ = effect of the kth location in the jth direction within the ith contract

$\delta_{(ijk)}$ = restriction error

P_ℓ = effect of the lth Roadmeter pass

$CP_{i\ell}$ = effect of the interaction of the ith contract by the lth Roadmeter pass

$DP_{(i)j\ell}$ = effect of the interaction of the jth direction in the ith contract by the lth Roadmeter pass

$LP_{(ij)k\ell}$ = effect of the interaction of the kth location in the jth direction within the ith contract by the lth Roadmeter pass

$\varepsilon_{(ijk\ell)}$ = within error, NID$(0,\sigma^2)$.

The results obtained from the analysis of variance in Table 3.1 indicated that for asphalt pavement contracts on two-lane roads, no significant variations in pavement roughness were present between both directions of travel. In other words, for two-lane highways the difference in the measured roughness between both lanes was found to be small and of no statistical significance.

Based on the above result, it can be stated that for usual traffic conditions (i.e., 50-50 directional split), testing either lane is expected to provide adequate description of the roughness of the section under consideration. However, in areas with unusual directional traffic characteristics, testing should be performed in the lane carrying the heavier traffic in order to obtain a realistic estimate of the highway roughness.

The analysis of variance also showed that pass effects, as well as its interaction terms, are non-significant. This clearly indicated that the roughness count is independent of the number of Roadmeter passes on a given highway section. In other words, one Roadmeter pass is considered sufficient for estimating the roughness of the section under evaluation.

The above two results can involve substantial cost savings in terms of energy conservation, and optimum usage of the roughness measuring equipment which allows testing greater mileage during a testing day and, in turn, permits covering a greater number of highway contracts each testing season.

TABLE 3.1. ANOVA- ROUGHNESS, ASPHALT SECTIONS

SOURCE	DF	MS	F
C	3	29873732	
D	4	460115	< 1
L	16	720566	
ERROR	0	------	
P	2	4190	< 1
CP	6	10096	1.2
DP	8	8761	1.3
LP	32	6624	
ERROR	0	----	

C=CONTRACT , D=DIRECTION , L=LOCATION , P=PASS

TABLE 3.2. ANOVA- ROUGHNESS, OVERLAY SECTIONS

SOURCE	DF	MS	F
C	3	2000000	
D	2	244336	2.9
L	12	84719	
ERROR	0	-----	
P	2	7994	3.0 *
CP	6	2664	< 1
DP	4	4695	< 1
LP	24	5224	
ERROR	0	----	

* NONSIGNIF. AT .10

TABLE 3.3. ANOVA- ROUGHNESS, JRCP SECTIONS

SOURCE	DF	MS	F
C	3	2364760	
L	8	668498	
ERROR	0	------	
P	2	2495	< 1
CP	6	7190	2.8
LP	16	2593	
ERROR	0	----	

C=CONTRACT , L=LOCATION , P=PASS

TABLE 3.4. ANOVA- ROUGHNESS, CRCP SECTIONS

SOURCE	DF	MS	F
C	3	2937381	
L	8	634966	
ERROR	0	------	
P	2	2468	< 1
CP	6	14964	2.4
LP	16	6274	
ERROR	0	----	

C=CONTRACT , L=LOCATION , P=PASS

One way analysis of variance and Student-Newman-Keuls tests on the data revealed that the variation of pavement roughness from location to location along a highway contract section was significant. Therefore, an appropriate procedure would be to cover the entire contract, thereby obtaining a roughness count representative of the serviceability of the specific contract under evaluation.

The above results are illustrated in Figures 3.1 to 3.3. Figures 3.1 and 3.2 show typical roughness variation along asphalt contracts. Also, the variation in the measured roughness between both lanes of two-lane highways are shown. Figure 3.3 shows a comparison of the Roadmeter roughness output from the first pass to the average output from three passes. Figure 3.3 indicates the same result previously obtained from the ANOVA relative to the insignificant effects of repeated passes on the same highway section and that one pass is sufficient.

Overlay Pavements

Of the four contracts used for the analysis of the roughness of overlay pavements, two contracts were on two-lane highways. These two contracts were tested in both directions of travel, thereby giving a total of 12 one-mile test locations for the investigation of roughness variations on two-lane highways.

The analysis of variance is given in Table 3.2. The statistical tests for the directional variability of pavement roughness on two-lane highways indicated that the difference was non-significant (at .05 level). The tests also showed that no appreciable difference was found among repeated Roadmeter passes made on the same contract (non-significant at .10 level).

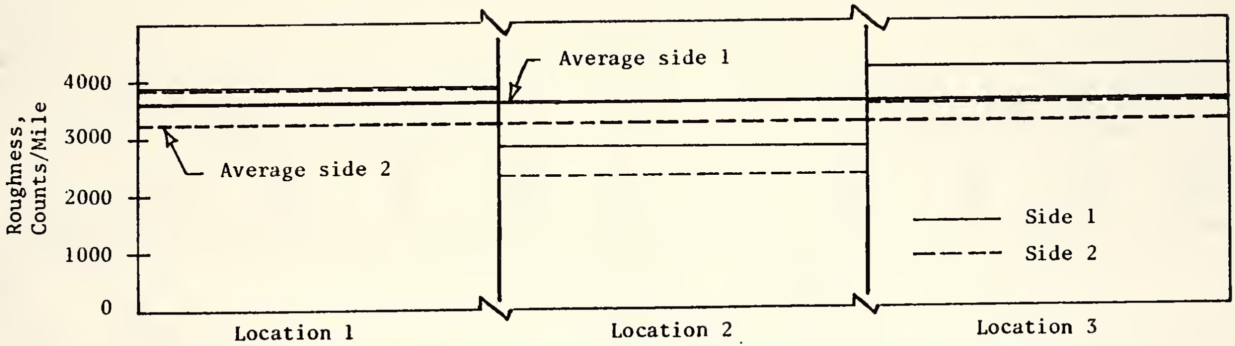

Figure 3.1. Variation of Pavement Roughness Along Contract 1 (Asphalt)

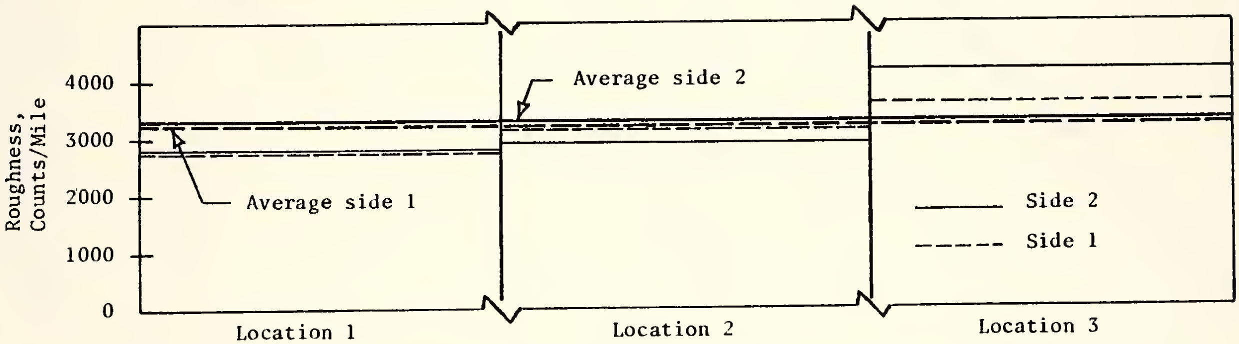

Figure 3.2. Variation of Pavement Roughness Along Contract 2 (Asphalt)

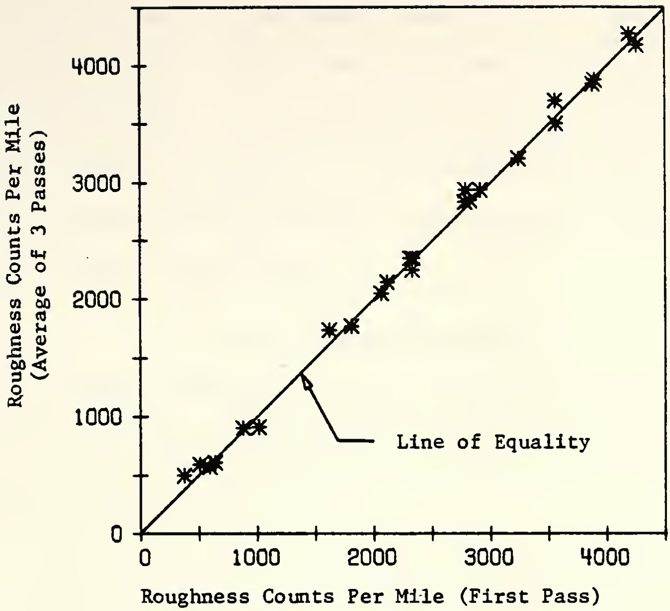

Figure 3.3. Roughness Counts from the First Pass vs. the Average of Three Passes - Asphalt Pavements

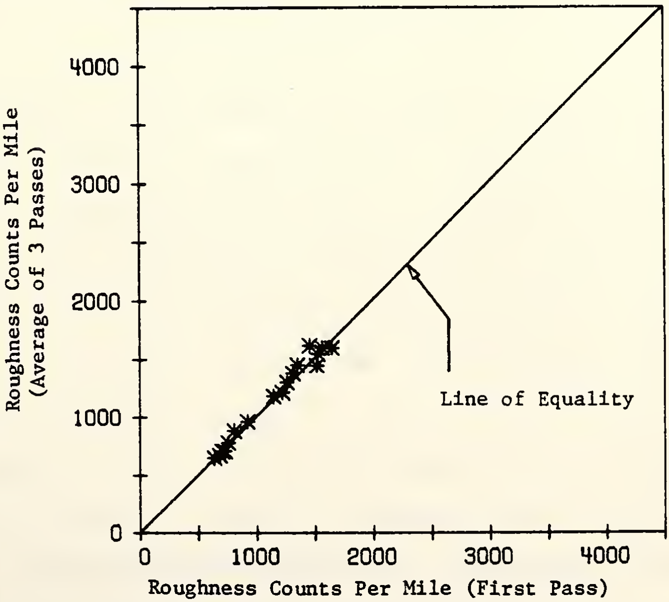

Figure 3.4. Roughness Counts from the First Pass vs. the Average of Three Passes - Overlay Pavements

Figures 3.5 and 3.6 show typical roughness variations along overlay pavement contract sections. The relationship between Roadmeter output from first pass and the average of three passes on overlay pavements is shown in Figure 3.4. It can be readily seen that the Roadmeter output from the first pass is almost equal to that obtained from the average of three passes.

Jointed Concrete Pavements

The analysis of variance model used for examining the effects of the factors involved in the evaluation of JRC pavement roughness variations took the form given below:

$$Y_{ijk} = \mu + C_i + L_{(i)j} + \delta_{(ij)} + P_k + CP_{ik} + LP_{(i)jk} + \varepsilon_{(ijk)} \qquad (3.2)$$

$$i=1,2,3,4 \quad j=1,2,3 \quad k=1,2,3$$

The terms have the same definitions as given in equation 3.1.

The results of the analysis (Table 3.3) were similar to those of asphalt and overlay pavements relative to the nonsignificant variation of the measured roughness from repeated Roadmeter passes on a given JRC contract. Also, one-way ANOVA and Newman-Keuls tests showed a significant variation in the measured pavement roughness from location to location along JRC contracts.

Figure 3.7 shows variations in roughness along a JRC contract section . Figure 3.9 compares the roughness output from three Roadmeter passes to the output from the first pass. As shown, the plotted points

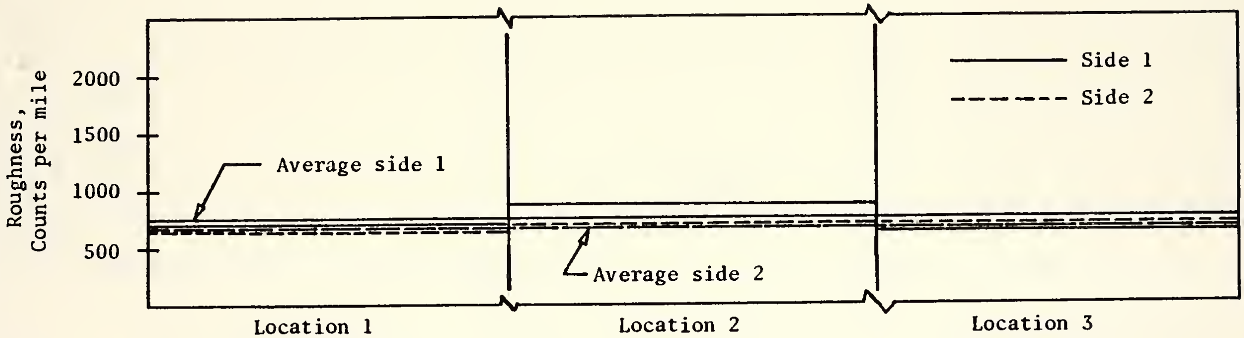

Figure 3.5. Variation of Pavement Roughness Along Contract 7 (Overlay)

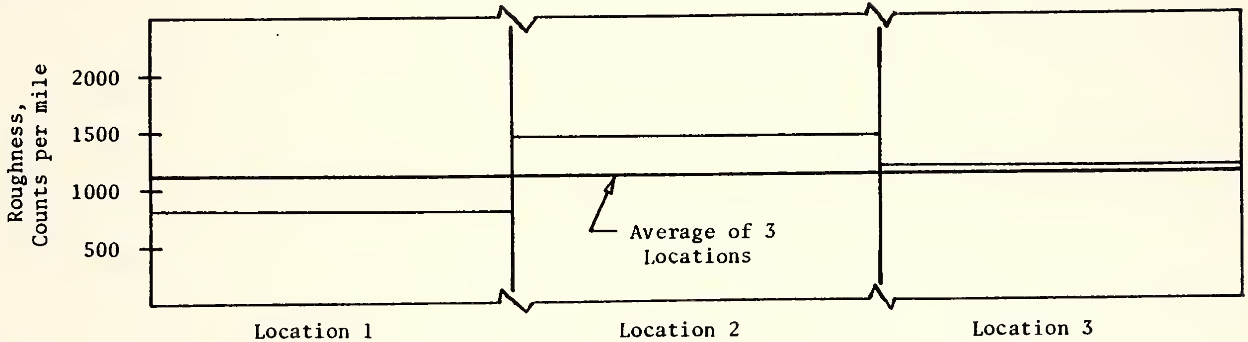

Figure 3.6. Variation of Pavement Roughness Along Contract 6 (Overlay)

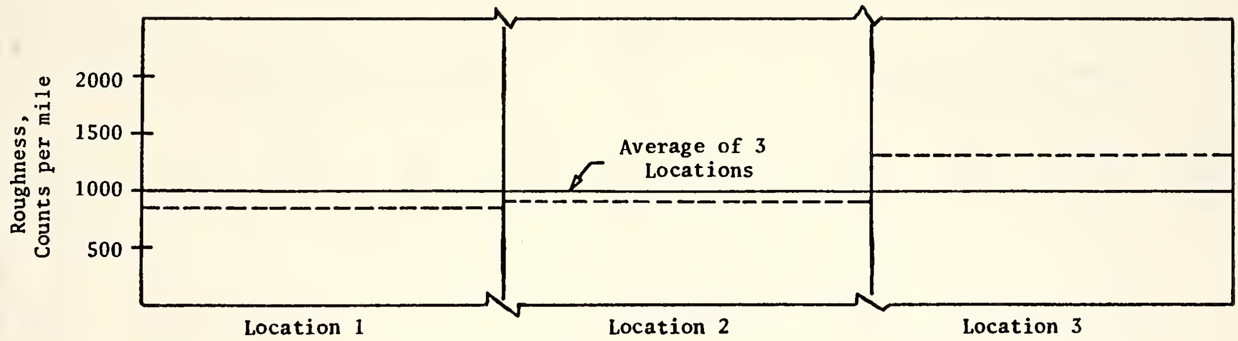

Figure 3.7. Variation of Pavement Roughness Along Contract 12 (JRC Pavement)

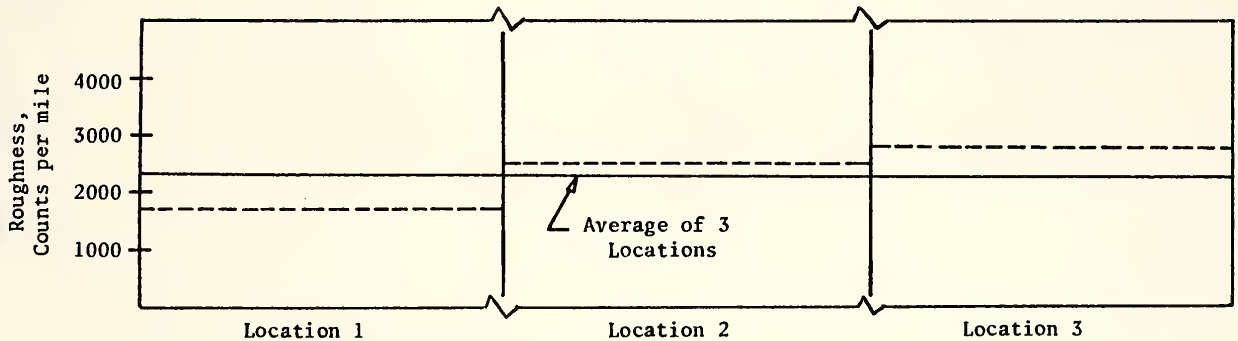

Figure 3.8. Variation of Pavement Roughness Along Contract 15 (CRC Pavement)

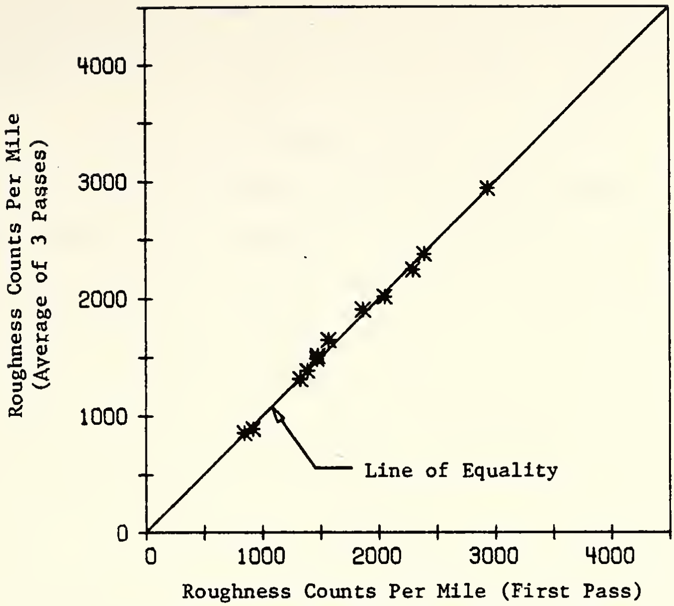

Figure 3.9. Roughness Counts from First Pass vs. the Average of Three Passes - JRC Pavement

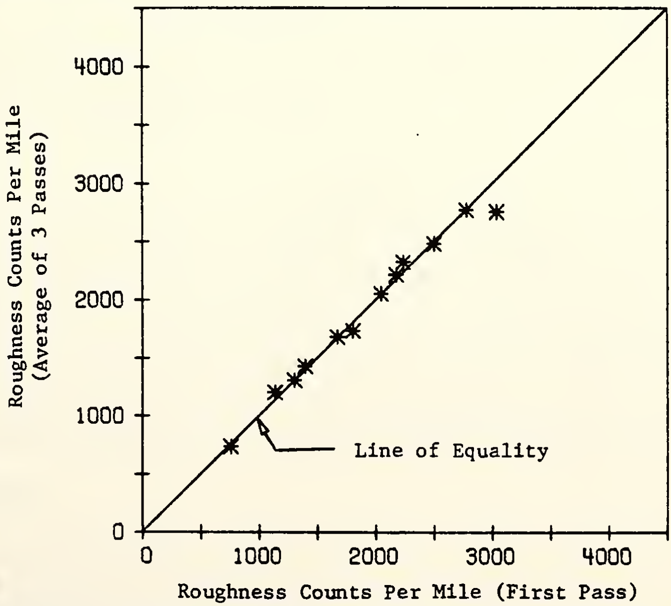

Figure 3.10. Roughness Counts from First Pass vs. the Average of Three Passes - CRC Pavement

are very close to the line of equality indicating that one Roadmeter pass over the contract gives an accurate estimate of its roughness.

Continuously Reinforced Concrete Pavements

The analysis of roughness variations on CRC pavements was made using the model given in equation 3.2. The ANOVA results are summarized in Table 3.4. Additional one-way and Newman-Keuls analyses were made for examining location effects.

Figure 3.8 shows an example of the measured roughness on a continuously reinforced concrete pavement. The results of the analyses mentioned above indicate that roughness values measured on different locations on a CRC contract were appreciably different. However, repeated Roadmeter passes on the same section were found to give statistically similar roughness values (i.e., pass effects non-significant). This is shown graphically in Figure 3.10 which compares the roughness output from the first pass to the average of three passes and, again, the differences were minor.

Summary

Pavement roughness is a phenomenon manifested at the pavement surface and is a function of the profile of the road surface. The main concern of this chapter was to develop an understanding of roughness variations along highway contract sections in order to arrive at the optimal procedure for conducting roughness measurements using the Roadmeter.

The analysis showed that for all the four pavement types included in the study, roughness varied significantly from location to location along contract sections. Therefore, in order to obtain a representative estimate of the serviceability of a highway contract, the measurements need to be conducted over the entire length of the contract under study.

The analysis also showed that repeated Roadmeter passes on a given highway contract section do not provide any additional accuracy to the measurements. Consequently, it is recommended that only one pass of the Roadmeter be made regardless of pavement type.

In addition, variations in pavement roughness between both sides of two-lane highways were found non-significant. Thus, it is recommended that two-lane highways be tested only in one direction. Judgment, based on experience with traffic patterns should be used for selecting the direction to be tested. It is of importance to mention that this conclusion is based on the results of data collected on asphalt and overlay pavements only.

Based on the above, the roughness measurements using the Roadmeter can be made on a continuous basis on consecutive highway contracts without a need to stop for retesting each contract. This allows conducting roughness mass inventories in an economical and practical way.

CHAPTER 4

SEASONAL VARIATIONS IN PAVEMENT SKID RESISTANCE

Skid resistance is usually measured by the force developed when a standard tire which is prevented from rotating slides along the pavement surface. Several means are available for measuring skid-resistance. The locked-wheel trailer method, in accordance with ASTM Method E 274 (34), is a widely accepted method.

Research on the slipperiness of pavement surfaces has been a subject of continuing research (8,20,39,54,56,61). The instruments used for skid resistance measurements are well standardized and documented in the literature (34,56). At present, the emphasis in the research is on the evaluation of short and long term variations of pavement skid resistance (13,22,36). Also, considerable research has been conducted on evaluating the effects of pavement type and composition on slipperiness (7,12,22,44).

Researchers involved in measuring skid resistance have long recognized that pavement surfaces undergo seasonal changes of frictional properties. These changes have been attributed to a complex interaction of seasonal influences, temperatures, rainfall, traffic, aggregate properties and mix designs. Several studies concluded that rainfall appeared to be a major cause of short-term variations in skid resistance (13,22,36). Also, aggregate characteristics and mix design were found to have significant influence on skid resistance variations (7,36).

Study Purpose

The purpose of this phase of the research study was to analyze data collected on a seasonal basis (fall and spring) from the pavements in this study to examine the variations in skid-resistance as measured by the locked-wheel skid trailer.

The Locked-Wheel Skid Trailer

The majority of highway agencies use locked-wheel skid trailers whose method has been standardized in ASTM E 274 (34). Figures 4.1 and 4.2 show the locked-wheel skid measuring system used in conducting skid resistance measurements in Indiana by ISHC Research and Training Center. Figure 4.3 shows a schematic of the main components of the skid tester.

The tractive force on a locked test wheel equipped with a bias-ply 7.5 x 14 tire is measured, by means of strain gages, as the locked wheel is dragged over a wetted pavement surface at a speed of 40 mph. This force is translated into the coefficient of friction which is multiplied by 100 and reported as a skid number (SN). The skid tester is an efficient piece of equipment which is capable of conducting statewide surveys of pavement skid resistance.

Data Collection

A total of 23 test sections, each 400 meters (0.25 mile) in length, were included in the seasonal testing program of pavement skid resistance. The measurements were made by personnel from ISHC Research and Training Center using the locked-wheel skid tester. A minimum of five tests were

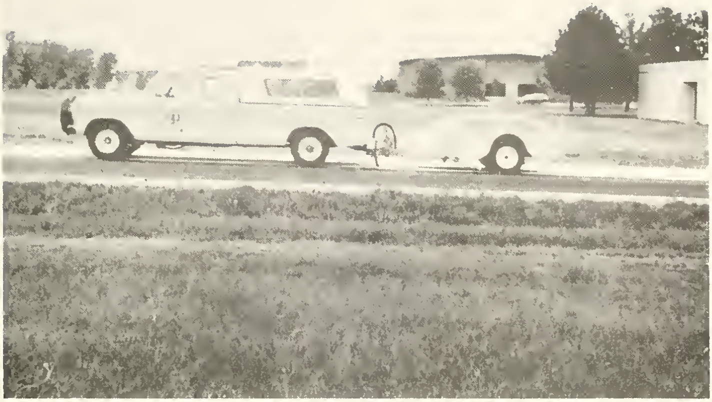

Figure 4.1. The Locked-Wheel Skid Tester

Figure 4.2. Applying Water to Pavement Ahead of the Test Wheel

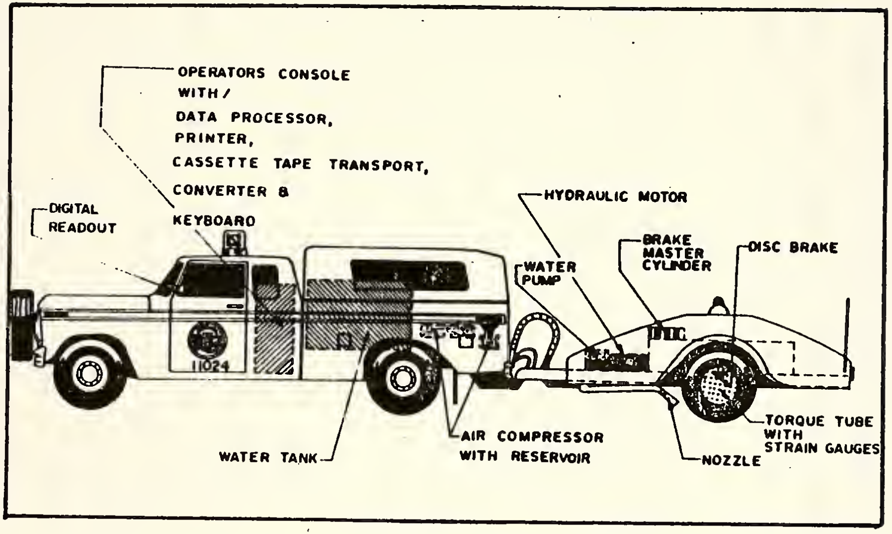

Figure 4.3. Schematic of the Locked-Wheel Skid Tester (Courtesy ISHC Research and Training Center)

made on each section at each visit.* The fall measurements were made in November, and the spring measurements in early May.

Data Analysis

The data collected on two surface types (asphalt and concrete) were analyzed using the model given by equation 2.1 in Chapter 2 with the measured skid number as the dependent variable. The following is a discussion of the results:

Asphalt Surfaces

The analysis of the data collected during the 1977-78 testing program showed a non-significant difference between the spring and fall skid numbers. The spring values, however, were slightly higher than the fall skid numbers. On the other hand, a significant difference in skid numbers was found between the fall of 1979 and the spring 1980 measurements with the spring values also being higher than the fall ones as can be seen from Figure 4.4.

The analysis of variance given in Table 4.1 showed that the skid resistance of test sections having asphalt surfaces did not experience significant changes between the two time periods considered in the analysis (1977-1978 vs. 1979-1980). Figure 4.4 depicts the time and seasonal changes in the skid resistance of asphalt surfaces.

The data as presented in Figure 4.6(a) indicated that, within the range of the data collected, the spring values are higher than the fall values by about 5-10 skid numbers.

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*Skid data are provided in Appendix D.

TABLE 4.1. ANOVA- SKID RESISTANCE, ASPHALT SURFACES

SOURCE	DF	MS	F
S	12	861.72	
ERROR	0	------	
T	1	298.79	5.8 **
ST	12	51.96	4.0 *
E	1	2160.79	24.1 *
SE	12	89.66	6.8 *
TE	1	1314.14	24.2 *
STE	12	54.41	
ERROR	224	13.14	

* SIGNIF. AT .01 ** NONSIGNIF. AT .04
S=SECTION , T=TIME , E=SEASON

TABLE 4.2. ANOVA- SKID RESISTANCE, CONCRETE SURFACES

SOURCE	DF	MS	F
S	8	984.45	
ERROR	0	------	
T	1	74.49	1.9
ST	8	39.34	2.5 **
E	1	440.55	9.4 **
SE	8	46.87	3.0 *
TE	1	612.25	12.7 *
STE	8	48.20	
ERROR	160	15.61	

* SIGNIF. AT .01 ** SIGNIF. AT .05
S=SECTION , T=TIME , E=SEASON

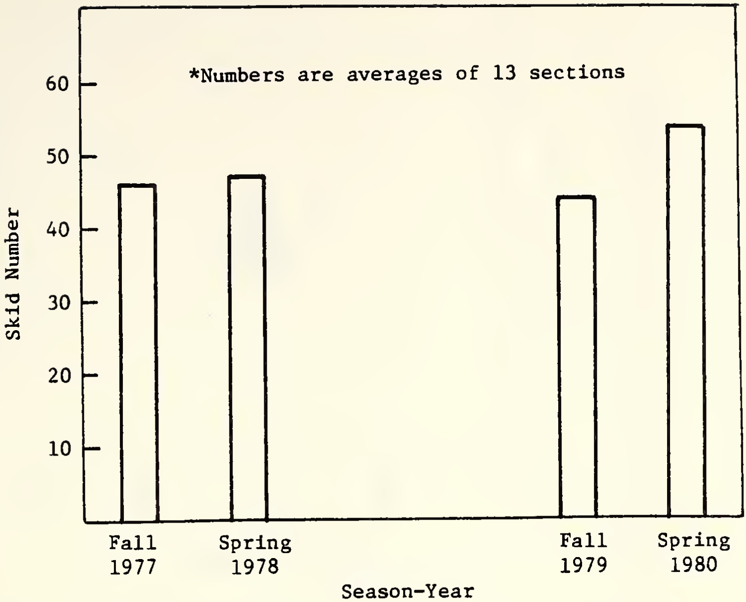

Figure 4.4. Changes in the Measured Skid Numbers - Asphalt Surfaces

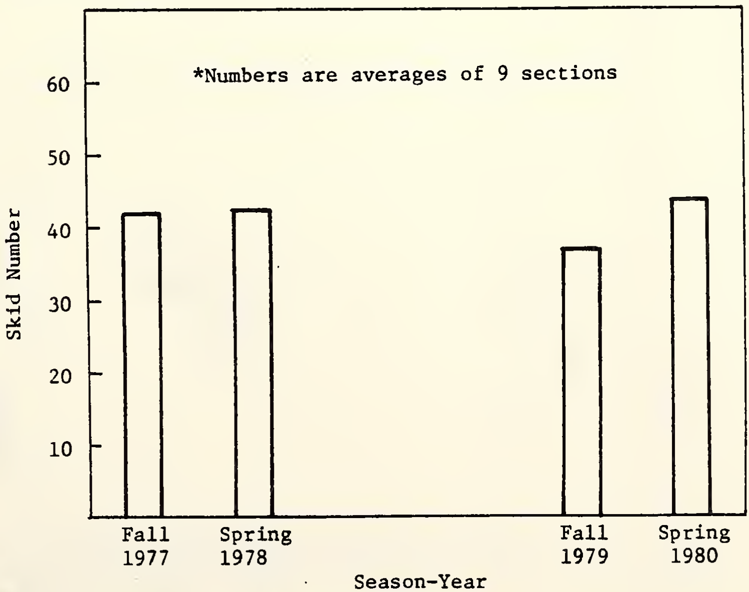

Figure 4.5. Changes in the Measured Skid Numbers - Concrete Surfaces

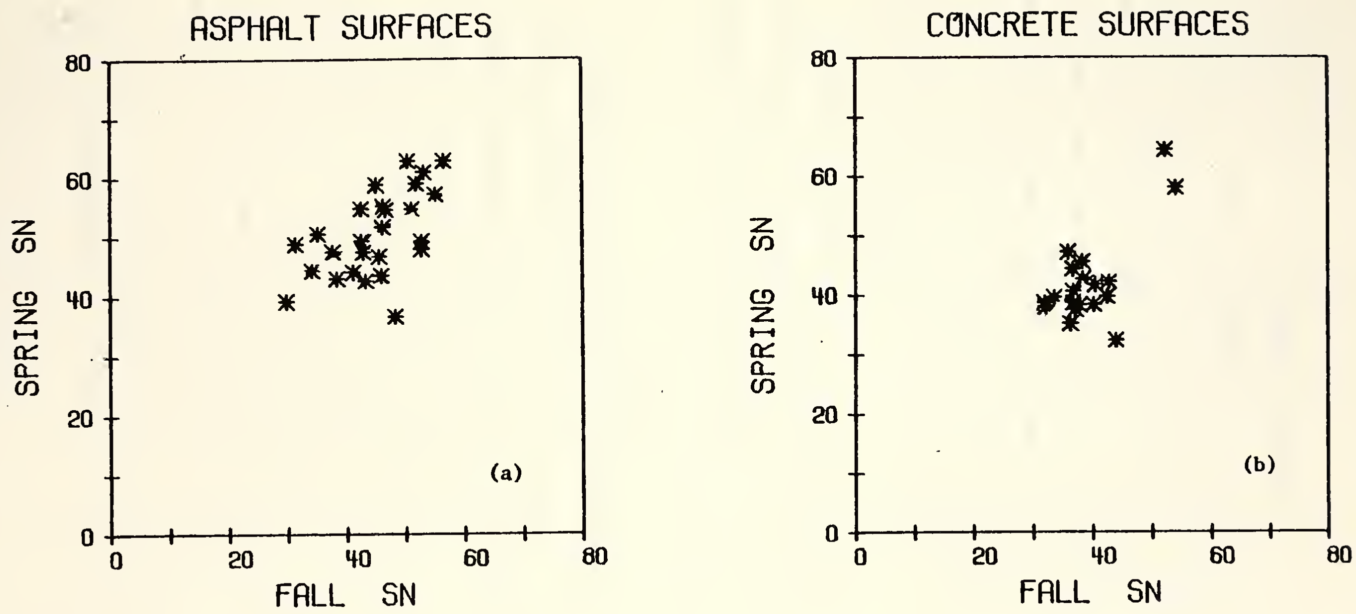

Figure 4.6. Relationship Between Spring and Fall Skid Numbers (a) Asphalt Surfaces; (b) Concrete Surfaces

Concrete Surfaces

Figure 4.5 shows the general time and seasonal changes in the skid resistance of concrete test sections. It was found that although the difference between the 1977 fall and 1978 spring measurements was very small, an appreciable difference was found between the 1979 fall and 1980 spring measurements. The analysis of variance given in Table 4.2 showed that there was no appreciable change in the skid numbers between the two time periods considered in the analysis (i.e. 1977-1978 vs. 1979-1980).

Figure 4.6(b) shows a plot of the data obtained from the study test sections. The difference between the spring and fall values appeared to be about five skid numbers.

Summary

In this chapter the seasonal differences in the skid resistance of asphalt and concrete surfaces were examined. Also, the time changes in the skid numbers during the period of this research were examined by means of analysis of variance techniques.

The results of the analysis indicated that the seasonal changes have significant influences on the skid resistance of both asphalt and concrete surfaces. Skid numbers measured in the spring appeared to be higher than those measured in the fall by about 5-10 SN for asphalt surfaces and by about 5 SN for concrete surfaces.

It is of interest to mention that these results agree with the results of a study made in the state of Illinois (16) which reported that test results in spring or early summer for asphalt surfaces were higher than in fall by 5-10 SN.

CHAPTER 5

VARIABILITY OF PAVEMENT SKID RESISTANCE OVER CONTRACT SECTIONS

The National Emphasis Program, as set forth in the Highway Safety Program Management Guide (25) provides that each state should develop a skid accident reduction program through the application of a systematic plan for the identification and rectification of slippery areas. Consequently, all states conduct friction testing programs on a routine basis (45). These programs are basically of two types: (1) accident related and (2) routine surveys. The most common measuring equipment is the locked-wheel skid trailer essentially using the standard ASTM 274 Method (34).

Study Objective

The objective of this phase of the study was to collect and analyze skid data from in-service pavements in Indiana in order to examine the variations of the measured skid numbers along highway contract sections. Creating an understanding of the nature of this variability would provide a useful input to the process of determining the optimum procedure for conducting pavement skid resistance mass inventories on a statewide basis using skid trailers.

Study Design

The experiment used for the collection and analysis of the data for this phase of the study was designed such that the variation of skid numbers between different locations within a contract can be evaluated. In addition, the experiment allowed examining the variation in skid numbers between both directions of travel for contracts on two-lane highways.

Twelve contracts were selected for the skid study representing the four pavement types considered in the research. The geographic locations of these contracts are given in Appendix E. Three one-mile test locations were selected within each contract and marked for testing operations.

Field Data Collection

Skid measurements were made using the locked-wheel skid trailer owned by ISHC Research and Training Center. A total of 15 tests were made on each one-mile test location. All the skid data were collected in July 1980. The data are presented in Appendix E.

Data Analysis

Asphalt Pavements

As mentioned earlier, the experiment was designed to evaluate the variation of measured skid numbers from location to location along a contract and to examine the variations between the two directions of travel on two-lane highways. The model employed in the analysis took the following form:

$$Y_{ijk\ell} = \mu + C_i + D_{(i)j} + L_{(ij)k} + \varepsilon_{(ijk)\ell} \qquad (5.1)$$

$$i=1,2,3 \quad j=1,2 \quad k=1,2,3 \quad \ell=1,2,\ldots,15$$

where

$Y_{ijk\ell}$ = measured skid number at the lth point in the kth location in the jth direction of the ith contract.

μ = overall mean

C_i = effect of the ith contract

$D_{(i)j}$ = effect of the jth direction (of the two-lane highway) in the ith contract

$L_{(ij)k}$ = effect of the kth location in the jth direction within the ith contract

$\varepsilon_{(ijk)\ell}$ = within error, NID $(0,\sigma^2)$.

The analysis of variance results given in Table 5.1 showed that for two-lane highways, the variation in the measured skid numbers between the two lanes was nonsignificant at α = .10. On the other hand, the variation in skid numbers from location to location within a contract was found to be significant at α = 0.01. This indicates that when testing two-lane asphalt pavement highways, greater emphasis should be placed on evaluating the skid resistance along the contract under evaluation than on evaluating the differences between the two sides of the highway by performing the tests in both directions of travel.

Therefore, it is felt that testing one direction on two-lane highways can provide representative values of the skid resistance on the highway. Testing one direction only is advantageous, practically speaking, relative to conducting pavement skid resistance mass inventories on a statewide basis since the skid tester can make the measurements on a given contract, then proceed to the next contract

TABLE 5.1. ANOVA- SKID, ASPHALT SECTIONS

SOURCE	DF	MS	F
C	2	1236.00	
D	3	454.00	2.4 **
L	12	187.00	5.1 *
ERROR	252	36.58	

* SIGNIF. AT .01 ** NONSIGNIF. AT .10
C=CONTRACT , D=DIRECTION , L=LOCATION

TABLE 5.2. ANOVA- SKID, OVERLAY SECTIONS

SOURCE	DF	MS	F
C	2	10597.0	
D	2	456.8	2.8 **
L	10	165.7	13.1 *
ERROR	210	12.6	

* SIGNIF. AT .01 ** NONSIGNIF. AT .10
C=CONTRACT , D=DIRECTION , L=LOCATION

TABLE 5.3. ANOVA- SKID, JRCP SECTIONS

SOURCE	DF	MS	F
C	2	2365.00	
L	6	128.70	6.8 *
ERROR	125	19.04	

* SIGNIF. AT .01
C=CONTRACT , L=LOCATION

TABLE 5.4. ANOVA- SKID, CRCP SECTIONS

SOURCE	DF	MS	F
C	2	336.0	
L	6	398.75	16.3 *
ERROR	126	24.47	

* SIGNIF. AT .01
C=CONTRACT , L=LOCATION

without a need to turn around for testing the reverse lanes and then turning around again and proceeding to test the next contract. Thus, considerable savings may be realized in the equipment as well as the time required to make the measurements.

Intensity of Skid Measurements on Asphalt Pavements

An example of skid resistance variability on an asphalt pavement contract is shown in Figure 5.1. The figure also depicts the skid resistance variations between both sides of a two-lane highway. It can be seen from Table 5.1 that $\hat{\sigma}^2 = 36.58$. Consequently, the standard error of a 1-mile location mean skid number is $(\frac{36.58}{n})^{1/2}$, where n is the number of skid tests per mile. The error, e, in estimating the mean skid number can then be obtained from the following equation (41):

$$e = \pm t_{\alpha/2}\sqrt{\frac{\hat{\sigma}^2}{n}} \tag{5.2}$$

where

e = error in the estimated SN of a one-mile test location

n = number of skid tests per mile

$\hat{\sigma}^2$ = within error

$t_{\alpha/2}$ = value obtained from the statistical tables (α=.10).

Figure 5.2 provides the relationship between the number of skid tests per mile and the corresponding error in estimating the skid resistance. This relationship can be used to select the required testing intensity depending on the desired accuracy.

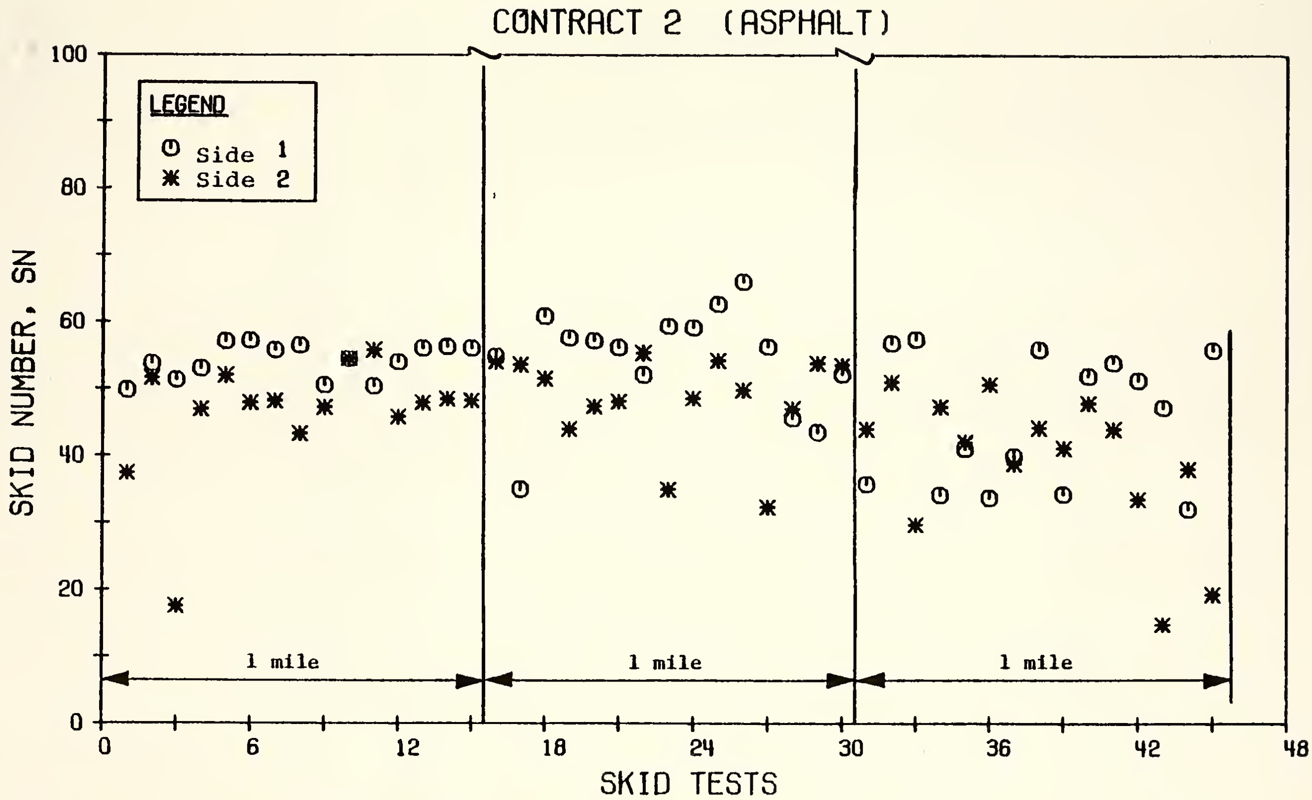

Figure 5.1. Typical Variations in Measured Skid Numbers Along an Asphalt Pavement Contract Section

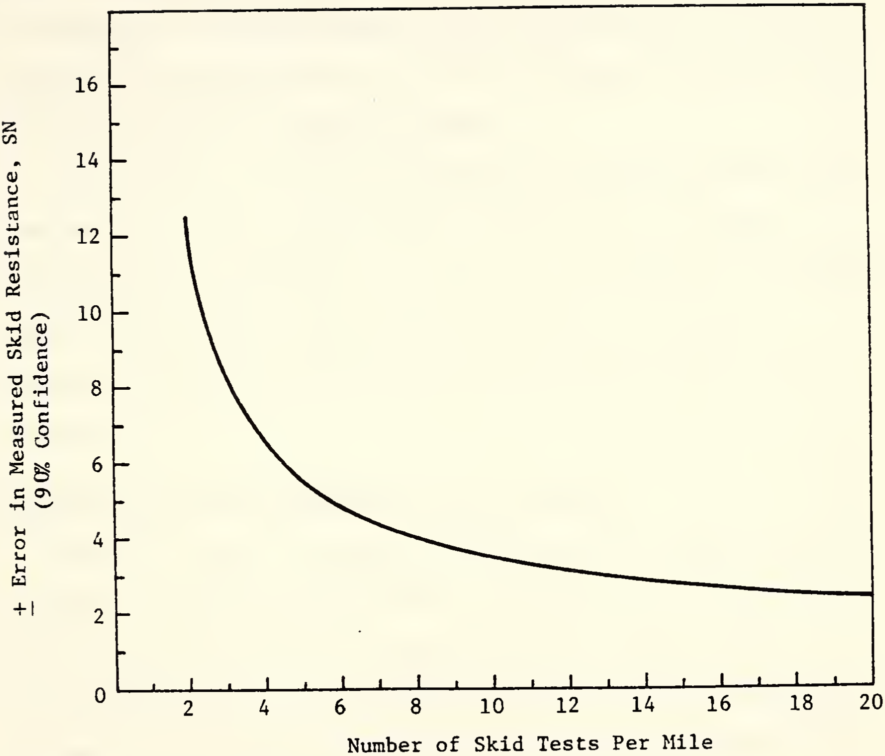

Figure 5.2. Error in Measured Skid Resistance vs. Number of Tests Per Mile (Asphalt Pavements)

Overlay Pavements

The analysis of direction and location effects on the measured skid numbers on overlay pavement contracts was made using the model shown in equation 5.1. The results as given in Table 5.2 showed that the variation of the skid numbers between the two sides of two-lane highways was nonsignificant at $\alpha = 0.10$. This result is similar to that previously obtained for asphalt pavements.

The variation of pavement skid resistance among the various locations within a contract was found to be significant at .01 level. Consequently, it is necessary to perform the measurements on the entire length of the contract being evaluated in order to obtain skid resistance values indicative of the various locations within the contract.

Intensity of Skid Measurements on Overlay Pavements

Figure 5.3 shows an example of the variations of skid numbers on an overlay pavement contract section. From Table 5.2 it can be seen that the standard error of a location mean SN is equal to $(\frac{12.6}{n})^{1/2}$. Using equation 5.2, the relationship between the error in estimating the mean SN and the number of skid tests per mile was established as shown in Figure 5.4. This relationship can be used for determining the required skid testing intensity corresponding to a given acceptable error.

Jointed Concrete Pavements

The model employed for analyzing the factors involved in the evaluation of pavement skid resistance of JRCP assumed the following form:

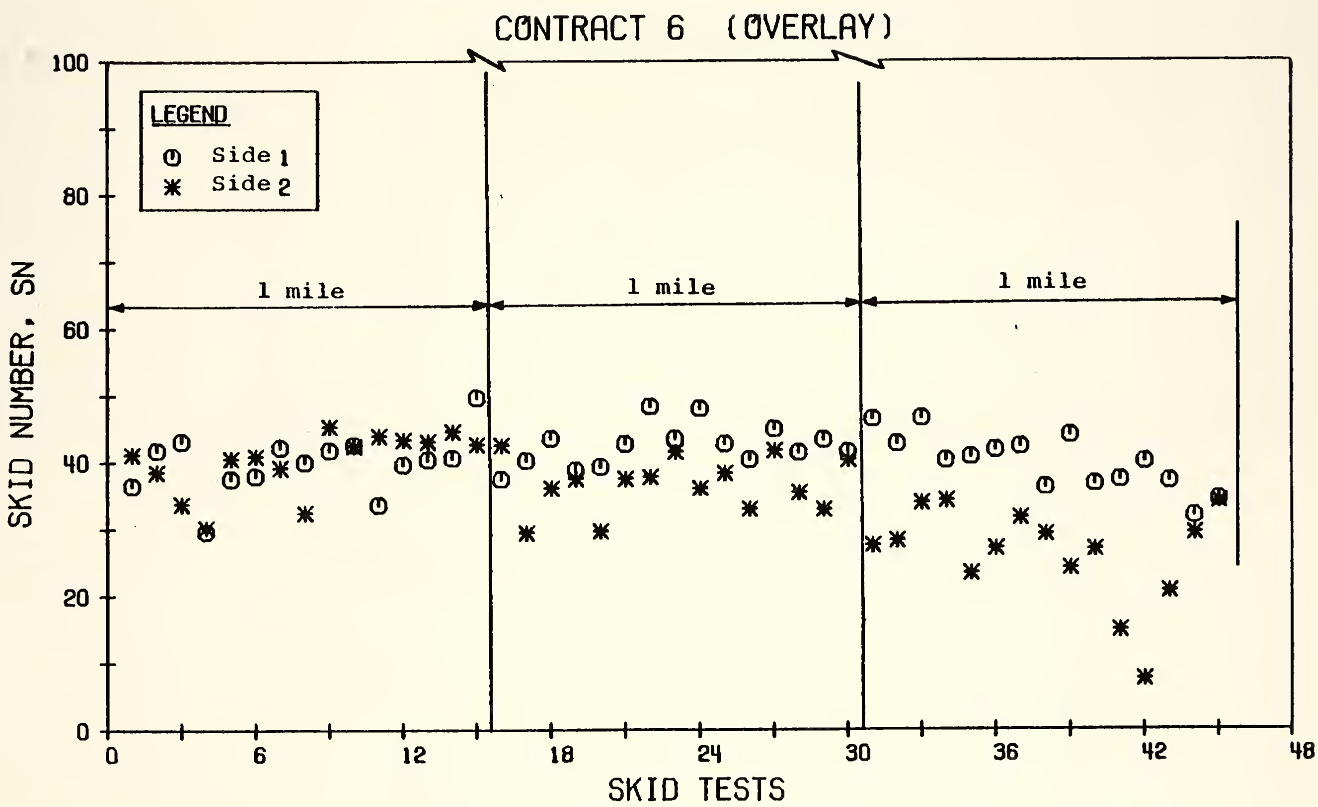

Figure 5.3. Typical Variations in Measured Skid Numbers Along an Overlay Pavement Contract Section

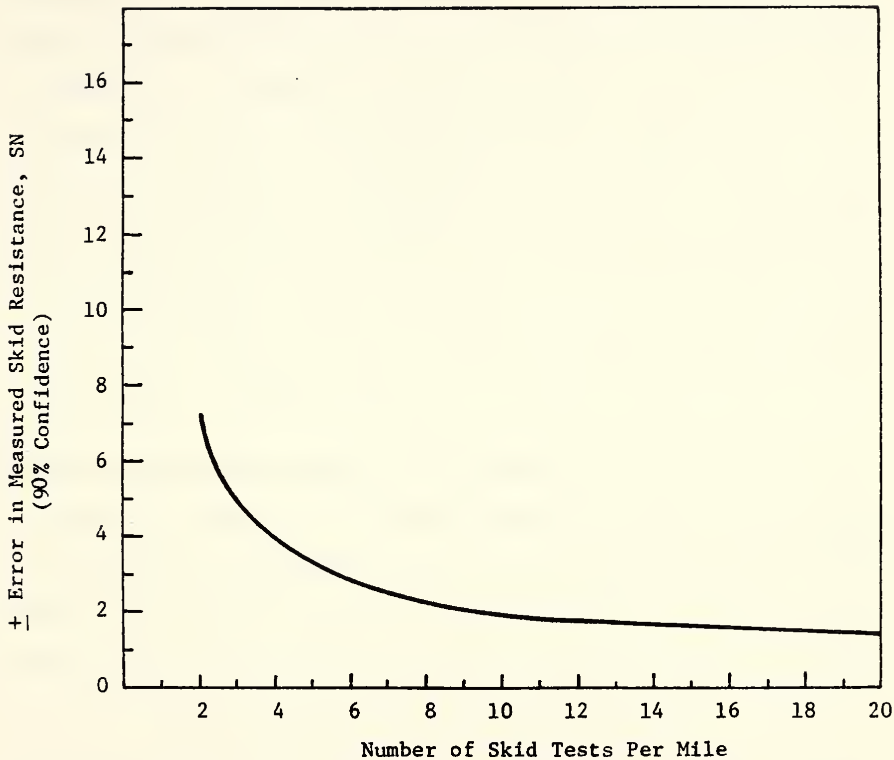

Figure 5.4. Error in Measured Skid Resistance vs. Number of Tests Per Mile (Overlay Pavements)

$$Y_{ijk} = \mu + C_i + L_{(i)j} + \varepsilon_{(ij)k} \tag{5.3}$$

$i=1,2,3 \quad j=1,2,3 \quad k=1,2,3,\ldots,15$

The definitions of the terms in the above model are the same as in equation 5.1. An analysis of variance was made of the data and the results are given in Table 5.3. It was found that JRC pavements were not different from asphalt and overlay pavements in the sense that appreciable variations in the measured skid numbers were found to exist on the different test locations within a contract. This indicates that for obtaining a clear picture of the skid resistance on JRC pavements the measurements should be distributed on the whole length of the section being evaluated. Figure 5.5 gives an example of the variations in skid numbers on a JRCP contract.

Intensity of Skid Measurements on JRC Pavements

Figure 5.6 shows the relationship between the number of skid tests per mile and the corresponding error in estimating the mean skid number. It provides a flexibility in selecting an appropriate testing intensity depending on the desired level of accuracy.

Continuously Reinforced Concrete Pavements

The model given in equation 5.3 was used for the analysis of skid variations over CRCP contracts. The results of the analysis are summarized in Table 5.4 which indicated that skid resistance can have appreciable variations over CRC contract sections. An example of skid resistance variations on a CRCP contract test locations is given in Figure 5.7. Therefore, the friction measurements on CRC pavements should be made over the entire length of the contract under evaluation.

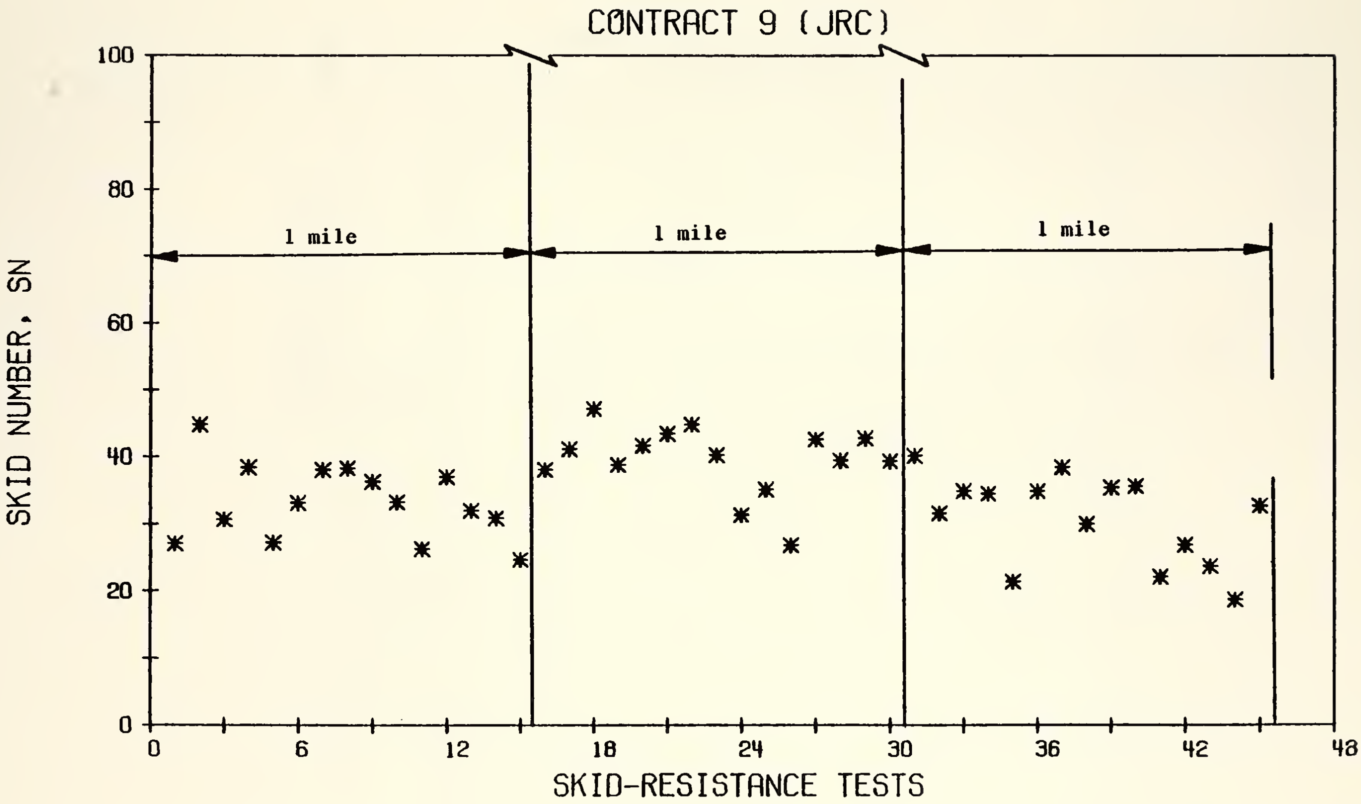

Figure 5.5. Typical Variations in Measured Skid Numbers Along a JRC Pavement Contract Section

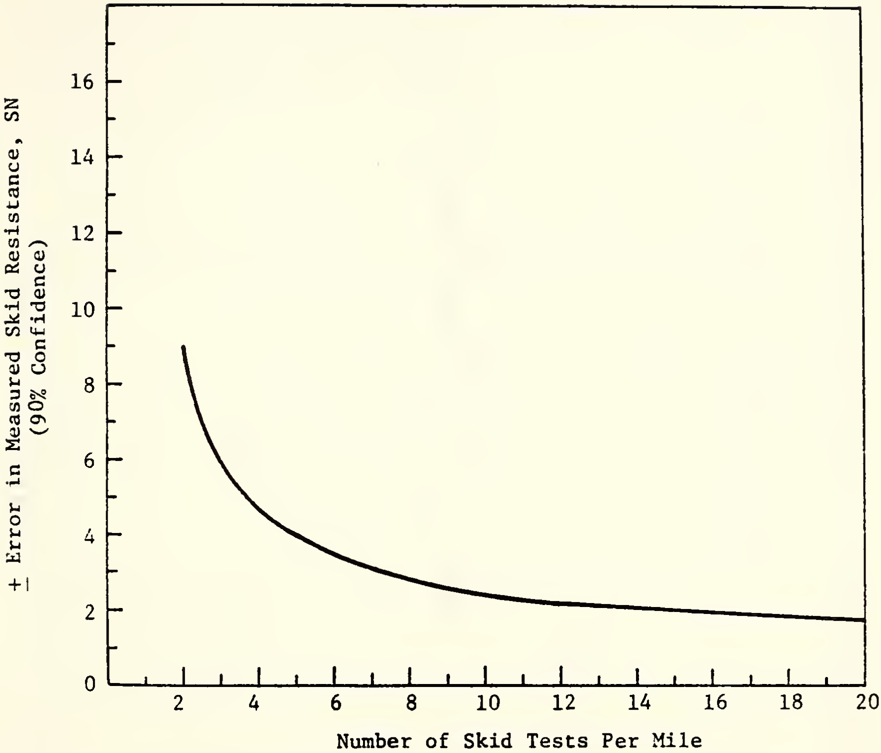

Figure 5.6. Error in Measured Skid Resistance vs. Number of Tests Per Mile (JRC Pavements)

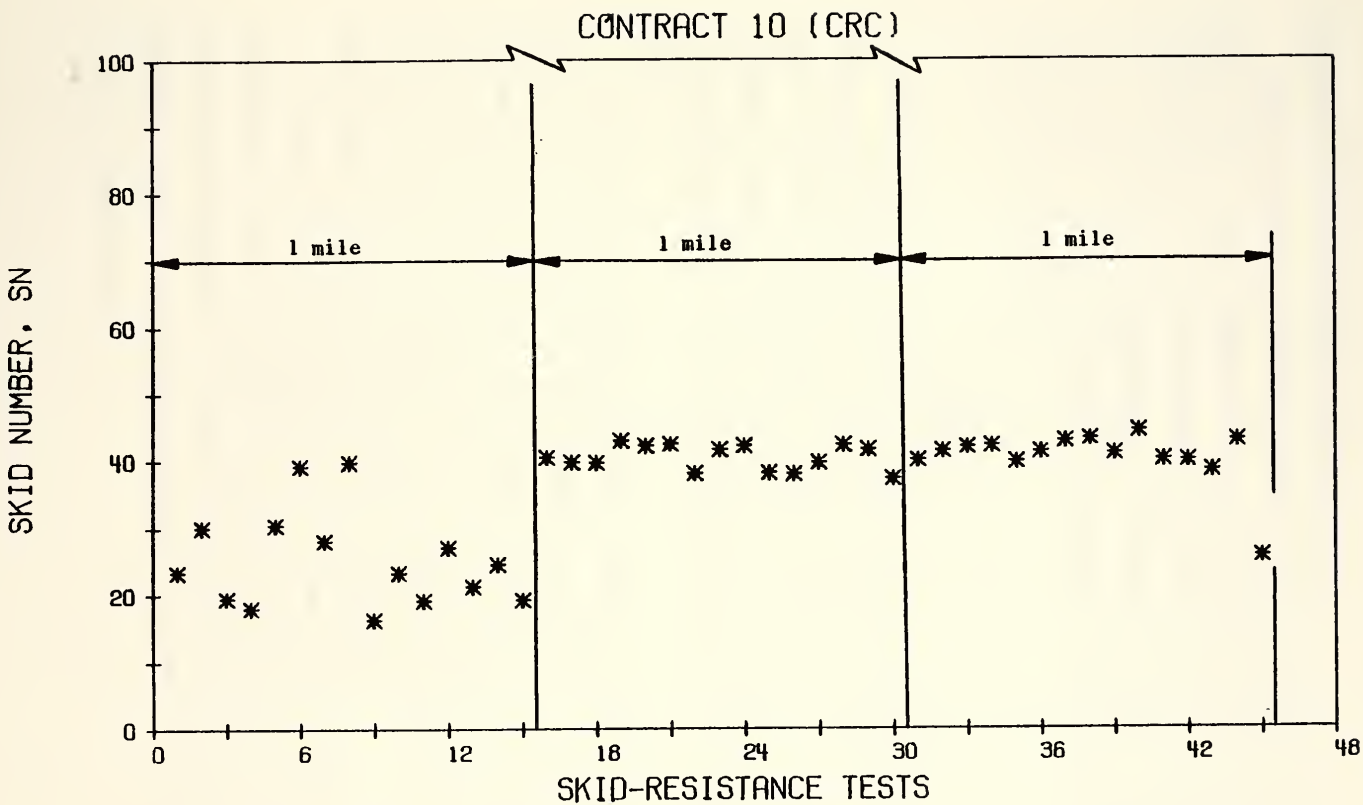

Figure 5.7. Typical Variations in Measured Skid Numbers Along a CRC Pavement Contract Section

Intensity of Skid Measurements on CRC Pavements

Figure 5.8 depicts the relationship between the number of skid tests per mile on CRC pavements and the corresponding error in the mean skid number. This relationship was established from the estimate of the variation of the measurements as obtained from Table 5.4 and using equation 5.2. Based on this relationship, an appropriate testing intensity can be selected.

Summary

The objective of this phase of the study was to collect and analyze skid resistance data according to a designed experiment in order to develop an understanding of the variations of the skid numbers on highway contract sections and to reach at the relationship between the testing intensity and the corresponding error in the mean skid number.

The analysis of variance was used to examine the variations of skid numbers on contract sections representing the four pavement types included in this research. Skid numbers were found to experience significant variations from location to location within the same contract. However, the difference in SN between both lanes of two-lane highways was found to be generally nonsignificant.

Therefore, for proper evaluation of pavement skid resistance the measurements should be distributed over the entire length of the contract under evaluation. An appropriate testing intensity can be selected, depending on the desired accuracy, from the correlations provided in this chapter.

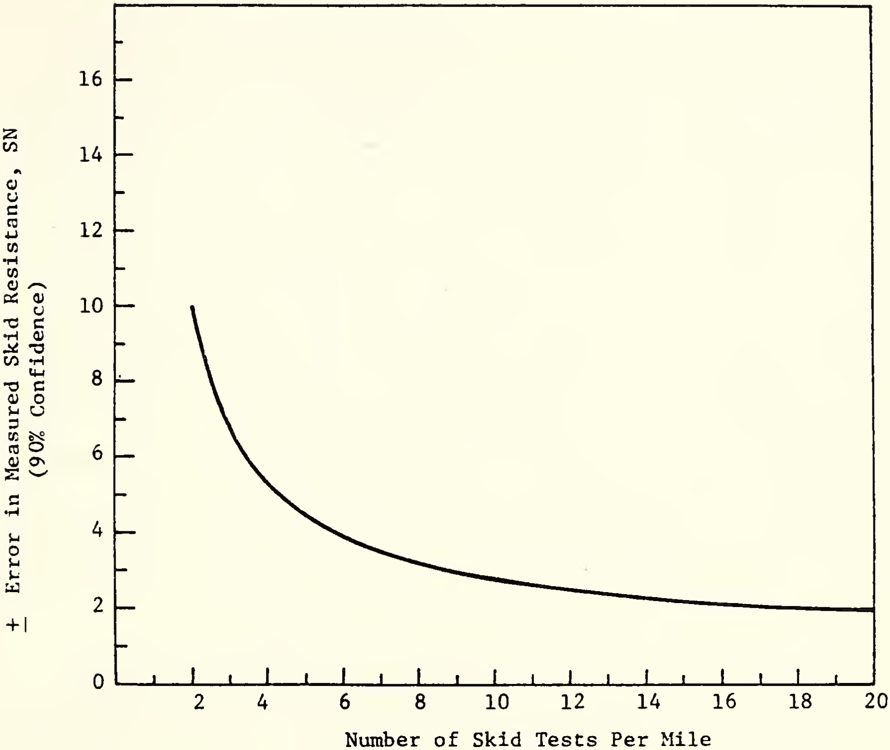

Figure 5.8. Error in Measured Skid Resistance vs. Number of Tests Per Mile (CRC Pavements)

CHAPTER 6

SEASONAL VARIATIONS IN PAVEMENT DEFLECTIONS

Friction and roughness measurements can be used to identify highway sections that need improvements. However, selecting the type and extent of the required improvement depends on the relative strength of the pavement structure.

Nondestructive evaluation of pavement structural adequacy involves measuring pavement deflections and analyzing them with respect to traffic. Research in several different areas in North America has established correlations between pavement allowable rebound deflections and repetitions of load (4,9,32,69). With these correlations, pavement deflections can be used to evaluate their structural adequacy and to design the thickness of overlays required to strengthen pavements.

Objective of Deflection Studies

The objective of this phase of the study was to examine the seasonal changes in the deflection parameters of each of the four pavement types included in the study by analyzing data collected on a seasonal basis from the study test sections.

Study Design

The study included four pavement types: 1) asphalt, 2) overlay, 3) JRC and 4) CRC pavements. The test sections were the same ones used by Mohan (42)*. Each section was 400 meters (0.25 mile) in length. These sections were essentially subsections of the larger sections (one-kilometer) used for roughness measurements.

The Dynaflect

A widely used piece of equipment for measuring pavement deflections is the Dynaflect shown in Figure 6.1 (51). The Dynaflect is mounted in a small two-wheel trailer towed behind a pick-up truck. Between test sites it travels on pneumatic tires at normal highway speeds. Upon arrival at a test site (Figure 6.2), a pair of steel load wheels are lowered to the pavement lifting the travel wheels and transmitting to the pavement an oscillating load generated by eccentric weights rotating eight revolutions per second. Pavement deflections are measured by means of a set of five sensors, as shown in Figure 6.2, and the output of the sensors is read directly on a digital computer screen installed beside the driver in the tow truck. The readings, in milli-inches (mils) of vertical deflection of pavement surface, are then recorded on the appropriate forms.

Deflection Basin Parameters

Figure 6.3 shows the Dynaflect sensor arrangement and the deflection basin. The shape of the deflection basin can be representative of the structural integrity and load carrying capacity of a pavement. Considerable research has been conducted on the use of the deflection

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*The geographic locations of these sections can be found in Table A1 of Appendix A. The data are summarized in Table F1 of Appendix F.

Figure 6.1. The Dynaflect and the Tow Truck

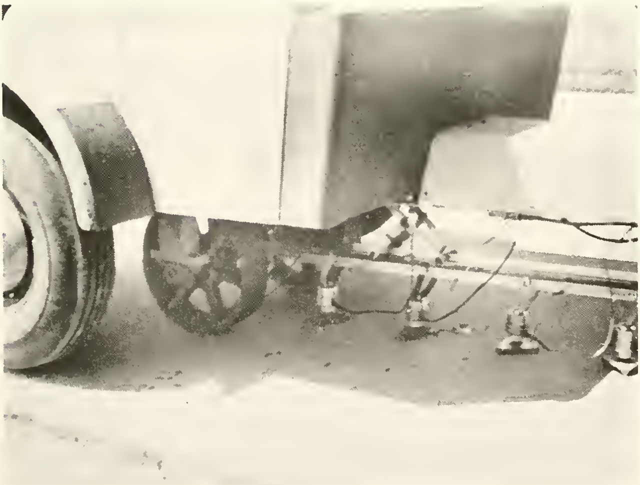

Figure 6.2. Close-up of the Sensors and Steel Wheels

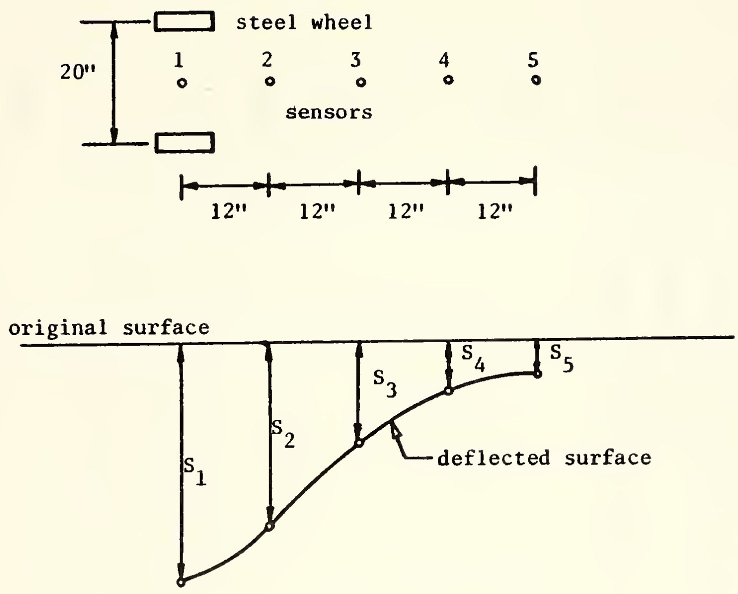

Figure 6.3. Dynaflect Sensor Arrangement and Deflection Basin (after NCHRP No. 76)

basin parameters in evaluating the structural adequacy of pavements (49,51,53,62). The following factors can be determined with the Dynaflect.

1. Dynaflect maximum deflection (DMD) which is the deflection at the center between the Dynaflect loading wheels as measured by the first sensor. This is the most commonly used parameter for evaluating the overall strength of the pavement system and designing overlays.

2. The surface curvature index (SCI) which is defined as follows

$$SCI = S_1 - S_2$$

where

S_1 and S_2 = readings of sensors number one and two, respectively.

The SCI is an indicator of the stiffness of the surface course. Stiffness decreases as SCI increases.

3. The spreadability parameter (SPD) is defined as the average deflection of all the sensors expressed as a percentage of the maximum deflection and is calculated as follows:

$$SPD = \frac{(S_1 + S_2 + S_3 + S_4 + S_5) \times 100}{5\ S_1}$$

where

S_1, S_2, S_3, S_4 and S_5 = readings of the five sensors.

The spreadability is a parameter which infers slab action of the pavement and the slab's ability to distribute load. Pavements with high SPD values distribute loads more effectively and, consequently, the resulting stresses and strains on the subgrade are smaller.

4. The base curvature index (BCI) and the fifth sensor (S_5) are also considered as two important deflection parameters which describe the pavement support conditions. The base curvature index, BCI, is calculated as

$$BCI = S_4 - S_5$$

where

S_4 and S_5 = readings of the fourth and fifth sensors, respectively.

The BCI parameter has been widely used for detecting problems in the subgrade and base layers. Studies indicated that the reading of the fifth sensor is indicative of subgrade support with higher S_5 values indicating weaker subgrades (38).

Data Collection

In the first phase of the study Dynaflect testing was conducted on 46 sections during the fall of 1977 and spring of 1978. The interim report concluded that deflection measurements taken in the outer wheel path are the critical ones and should be used for evaluation purposes. Therefore, in this phase of the study, the measurements were made in the outer wheel path only (3 feet from pavement edge). The testing was conducted on a seasonal basis, as before, during the fall of 1979 and spring of 1980. The tests were made at 20-meter intervals, thereby obtaining a total of 21 readings per section.

Based on a site survey on the study test sections, 11 sections were disqualified and, consequently, were dropped from the testing program.* During the first phase of this research, reported in the

*Some sections passed over bridges and others were at intersections with other highways.

interim report by Mohan (42), deflection measurements on jointed concrete pavements (JRC) and on overlay pavements were made at random (i.e., without regard to the presence of the joints in JRC pavements and reflection cracks in overlay pavements). Consequently, the analysis of the data collected on the overlay and jointed pavements was made without considering the position of test as a factor affecting the measurements on short test sections.

In this phase of the research, however, it was desired to check the validity of this approach. Therefore, the testing was performed during the spring of 1980 taking position of test into consideration.

On overlay pavements, deflections were measured at two positions: (1) the reflection crack and (2) mid-span. The crack measurement was always made at the downstream side of the crack with the Dynaflect steel wheels and the first sensor placed as close as possible to the crack. The mid-span reading was taken at a good part of the pavement where there was no cracking. Jointed concrete pavements were tested at three positions: (1) joint, (2) crack and (3) mid-span. Testing on overlay and JRC pavements was performed at 11 test stations on each section.

Data Analysis

Statistical Model

The data collected in the two phases of the study were analyzed using analysis of variance techniques (3) to examine the seasonal and time effects on the deflection parameters.

The model used in this analysis took the following form:

$$Y_{ijk\ell} = \mu + S_i + \delta_{(i)} + T_j + ST_{ij} + E_k + SE_{ik} + TE_{jk} + STE_{ijk} + \varepsilon_{(ijk)\ell} \quad (6.1)$$

$$i=1,2,\ldots,n \quad j=1,2 \quad k=1,2 \quad \ell=1,2,\ldots,21$$

where

$Y_{ijk\ell}$ = deflection parameter under consideration (DMD or SCI or SPD or S_5) at the lth test station measured in the kth season of the jth time period at the ith test section

μ = overall mean

S_i = effect of the ith test section

$\delta_{(i)}$ = restriction error

T_j = effect of the jth time period

E_k = effect of the kth test season

ST_{ij} = interaction of the ith test section with the jth test period

SE_{ik} = interaction of the ith test section with the kth test season

TE_{jk} = interaction of the jth time period and the kth test season

STE_{ijk} = interaction of the ith test section and the jth test period and the kth test season

$\varepsilon_{(ijk)\ell}$ = random error caused by the lth test on the ith section in the kth season in the jth period, NID $(0,\sigma^2)$

n = number of test sections included in the analysis.

Asphalt Pavements

The results of the analysis of variance for asphalt pavements are summarized in Tables 6.1 to 6.4. Figure 6.4 shows the changes in the deflection parameters of asphalt test sections.

From Table 6.1 it can be seen that the deflection of asphalt pavements experienced significant changes between the two time periods of the study (1977-1978 vs. 1979-1980). A general reduction in deflection was noticed between the two periods. Also, the test season (spring vs. fall) was found to have appreciable (significant) effects on the measured deflection. The deflection values were found to be higher in spring than in fall.

Despite this general behavior pattern, however, each of the test sections exhibited its own behavior with respect to time and season. In other words, there were variations in the amount of time and seasonal changes in deflections from section to section. These variations reflect the variability of the inherent characteristics of the different highway sections caused by different design, construction, material, age and traffic conditions. The significance of the section by season and section by time interactions (Table 6.1) reflect the variation in the behavior of individual highway sections, from the standpoint of measured deflections, relative to time and seasonal changes.

The other deflection parameters for asphalt pavements were also examined. It was found that seasonal variations had significant effects on the surface curvature index (SCI) as shown in Table 6.2.

TABLE 6.1. ANOVA- DMD, ASPHALT SECTIONS

SOURCE	DF	MS	F
S	8	3.074	
ERROR	0	-----	
T	1	5.352	27.6 *
ST	8	.194	27.7 *
E	1	4.618	13.3 *
SE	8	.347	49.6 *
TE	1	.432	1.8
STE	8	.244	
ERROR	718	.007	

* SIGNIF. AT .01
S=SECTION , T=TIME , E=SEASON

TABLE 6.2. ANOVA- SCI, ASPHALT SECTIONS

SOURCE	DF	MS	F
S	8	2.700	
ERROR	0	-----	
T	1	2.106	12.5 *
ST	8	.168	7.6 *
E	1	8.579	11.7 *
SE	8	.732	33.3 *
TE	1	1.230	6.4 **
STE	8	.193	
ERROR	718	.022	

* SIGNIF. AT .01 ** SIGNIF. AT .05
S=SECTION , T=TIME , E=SEASON

TABLE 6.3. ANOVA- SPD, ASPHALT SECTIONS

SOURCE	DF	MS	F
S	8	0.128	
ERROR	0	-----	
T	1	.051	10.0
ST	8	.005	5.0 *
E	1	.103	3.2
SE	8	.032	32.0 *
TE	1	.068	68.0 *
STE	8	.003	
ERROR	718	.001	

* SIGNIF. AT .01
S=SECTION , T=TIME , E=SEASON

TABLE 6.4. ANOVA- SS READING, ASPHALT SECTIONS

SOURCE	DF	MS	F
S	8	3.053	
ERROR	0	-----	
T	1	5.657	21.6 *
ST	8	.262	26.2 *
E	1	1.980	4.0 **
SE	8	.500	50.0 *
TE	1	.041	4.1 **
STE	8	.341	
ERROR	718	.010	

* SIGNIF. AT .01 **SIGNIF. AT .10
S=SECTION , T=TIME , E=SEASON

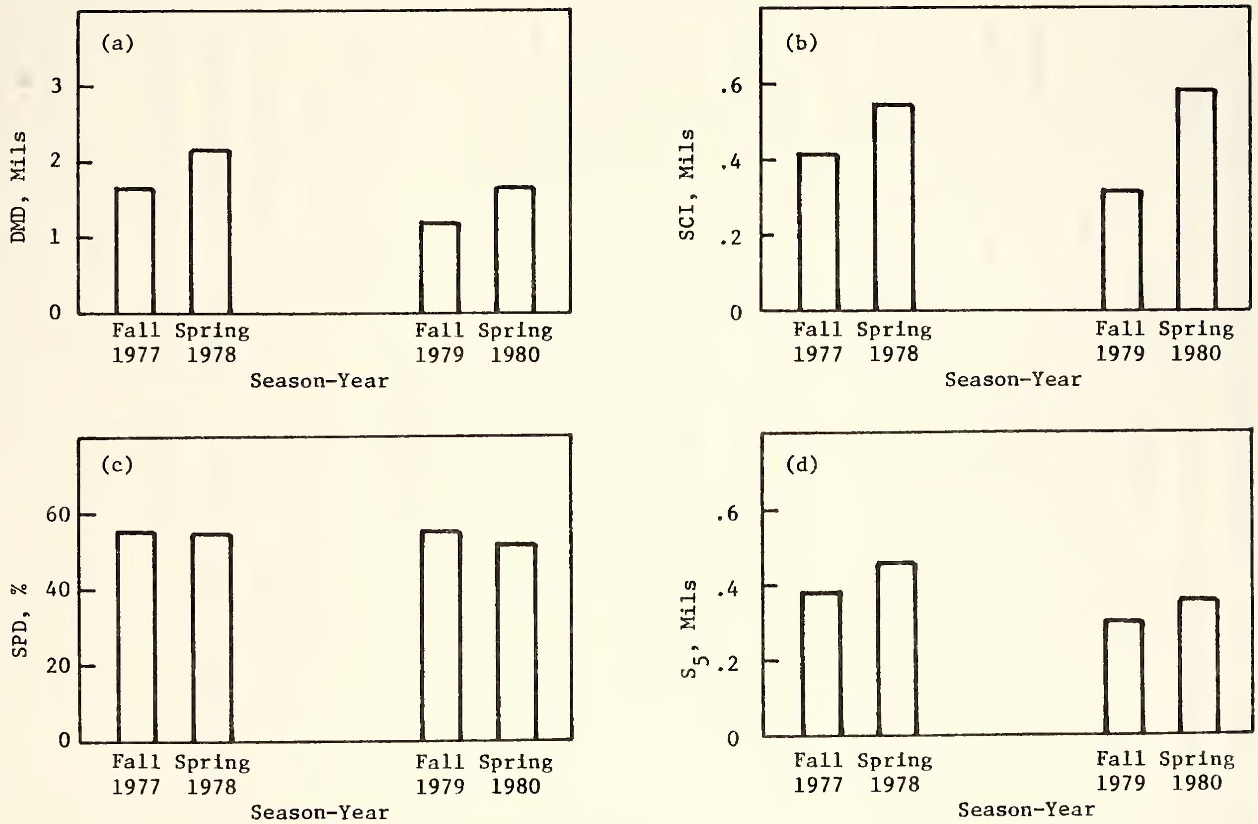

Figure 6.4. Changes in Deflection Parameters of Asphalt Pavement Test Sections
Note: Values are averages of 9 sections

Figure 6.4b shows that SCI in spring was higher than in fall, indicating a reduction in pavement stiffness during the frost melt period. It can also be noticed that the spring SCI increased with time which indicates a general reduction in pavement stiffness.*

As can be seen from Table 6.3 and Figure 6.4c, no significant changes in the spreadability parameter (SPD) occurred between 1977 and 1980. Also, the seasonal effects were found nonsignificant. However, the spring values of SPD were slightly less than the fall values, indicating a slight reduction in the ability of the pavement to distribute the loads.

The analysis of the S_5 parameter indicated that the support conditions underneath asphalt pavements experienced significant seasonal changes as well as time changes between 1977 and 1980 (Table 6.4 and Figure 6.4d). The S_5 spring values were higher than the fall values, indicating the weakening effects of the spring thaw period on pavement support conditions. Graphical plots of the data are given in Figure F1 in Appendix F.

Overlay Pavements

Effect of Test Position

As mentioned earlier, deflection testing during the spring of 1980 was made taking the position of test into consideration (i.e. the reflection crack vs. mid-span). The model used to examine the effect of testing position took the following form:

$$Y_{ijk} = \mu + S_i + \delta_{(i)} + P_j + SP_{ij} + \varepsilon_{ijk} \qquad (6.2)$$

$$i=1,2,\ldots,9 \quad j=1,2 \quad k=1,2,\ldots,11$$

*In the fall of 1979 average SCI was slightly less than in the fall of 1977 which may be due to temperature variations.

where

Y_{ijk} = deflection parameter under consideration (DMD or SCI or SPD or S_5) at the kth test point measured at the jth position in the ith test section

μ = overall mean

S_i = effect of the ith test section

$\delta_{(i)}$ = restriction error

P_j = effect of the jth test position

SP_{ij} = interaction of the ith test section with the jth test position

ε_{ijk} = random error, NID$(0,\sigma^2)$.

The analysis of variance as given in Tables 6.5 to 6.8 showed that for the short sections included in the seasonal testing the effect of the position of test on deflections was nonsignificant. Examples of the measured deflections on overlay pavement sections are given in Figure 6.5. Thus, it was decided that the data collected during the first phase of the research without regard to the effect of the position of test (42) can be used in the analysis of the seasonal effects.

Seasonal Changes in Overlay Pavement Deflections

The analysis of the deflection data collected on overlay pavement test sections, as summarized in Tables 6.9 to 6.12, indicated that the difference between the spring and fall deflections was significant. The spring values were higher than the fall ones. The spreadability parameter (SPD), however, did not exhibit appreciable seasonal variations.

TABLE 6.5. ANOVA- DMD, OVERLAY SECTIONS

SOURCE	DF	MS	F
S	8	1.546	
ERROR	0	-----	
P	1	0.080	< 1
ERROR *	172	0.138	

S=SECTION , P=POSITION OF TEST
* SP POOLED INTO ERROR TERM

TABLE 6.6. ANOVA- SCI, OVERLAY SECTIONS

SOURCE	DF	MS	F
S	8	0.365	
ERROR	0	-----	
P	1	0.011	< 1
ERROR *	172	0.105	

S=SECTION , P=POSITION OF TEST
* SP POOLED INTO ERROR TERM

TABLE 6.7. ANOVA- SPD, OVERLAY SECTIONS

SOURCE	DF	MS	F
S	8	4148.653	
ERROR	0	--------	
P	1	2277.891	1.3
SP	8	1805.662	1.5
ERROR	164	1174.637	

S=SECTION . P=POSITION OF TEST

TABLE 6.8. ANOVA- SS, OVERLAY SECTIONS

SOURCE	DF	MS	F
S	8	1.940	
ERROR	0	-----	
P	1	0.907	1.3
ERROR *	172	0.685	

S=SECTION . P=POSITION OF TEST
* SP POOLED INTO ERROR TERM

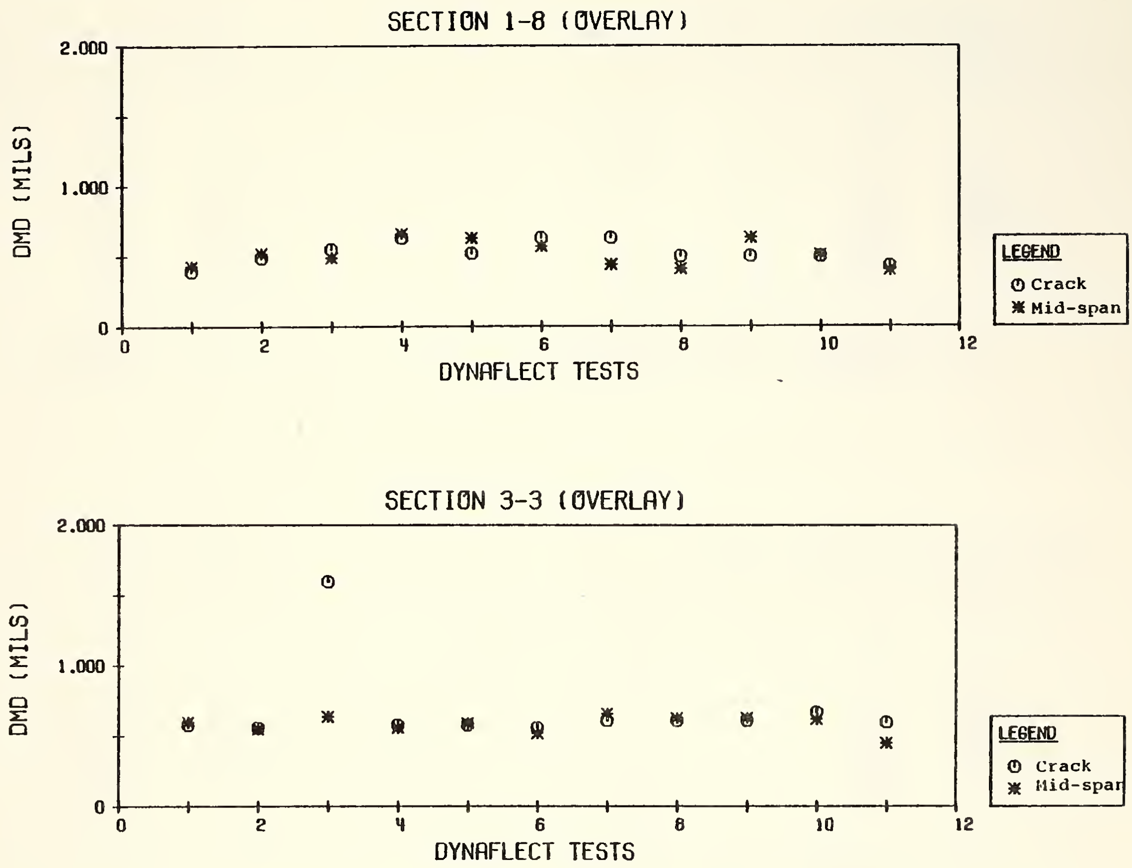

Figure 6.5. Typical Plots of Measured Deflections at the Crack and Mid-Span Positions on Overlay Pavements

TABLE 6.9. ANOVA- DMD, OVERLAY SECTIONS

SOURCE	DF	MS	F
S	4	.972	
ERROR	0	----	
T	1	11.766	31.4 *
ST	4	.375	15.6 *
E	1	7.181	87.6 *
SE	4	.082	3.4 *
TE	1	1.641	20.5 **
STE	4	.080	
ERROR	409	.024	

* SIGNIF. AT .01 ** SIGNIF. AT .05
S=SECTION , T=TIME , E=SEASON

TABLE 6.10. ANOVA- SCI, OVERLAY SECTIONS

SOURCE	DF	MS	F
S	4	.068	
ERROR	0	----	
T	1	.014	0.3
ST	4	.056	5.6 *
E	1	.256	9.9 **
SE	4	.026	2.6 **
TE	1	.090	9.0 **
STE	4	.057	
ERROR	409	.010	

* SIGNIF. AT .01 ** SIGNIF. AT .05
S=SECTION , T=TIME , E=SEASON

TABLE 6.11. ANOVA- SPD, OVERLAY SECTIONS

SOURCE	DF	MS	F
S	4	1179.300	
ERROR	0	--------	
T	1	33.752	< 1
ST	4	1858.440	4.7 *
E	1	951.810	< 1
SE	4	1981.437	5.0 *
TE	1	1.102	< 1
STE	4	1657.674	
ERROR	409	399.712	

* SIGNIF. AT .01
S=SECTION , T=TIME , E=SEASON

TABLE 6.12. ANOVA- S5 READING, OVERLAY SECTIONS

SOURCE	DF	MS	F
S	4	.626	
ERROR	0	-----	
T	1	7.330	23.6 *
ST	4	.311	13.5 *
E	1	4.924	13.1 **
SE	4	.376	16.4 *
TE	1	1.094	5.3 ***
STE	4	.205	
ERROR	409	.023	

* SIGNIF. AT .01 **SIG.AT .05 ***SIG. AT .10
S=SECTION , T=TIME , E=SEASON

A general observation was that the seasonal effects on the surface curvature index (SCI) and the S_5 parameter were generally more pronounced during the 1979-1980 period than during 1977-1978 period as can be seen from Figure 6.6.

Graphical plots showing the spring measurements as related to the previous fall measurements are given in Appendix F.

Jointed Concrete Pavements

Effect of Test Position

The model given in equation 6.2 was used to evaluate the effect of the test position on the deflections of JRC pavements. The analysis of the data indicated that the effect of test position on the measured deflections was statistically nonsignificant (Tables 6.13 to 6.16). Plots of the data are shown in Figure 6.7. It can be seen that the deflections measured at each of the three positions do not take definite characteristic patterns, but rather, they vary from location to location. For example, it can be seen that the deflection of any test position can be higher at one location whereas the deflection of another test position is higher at another location. Based on this result it was decided to use Mohan's data (42) in the analysis of seasonal changes of JRC pavement deflections.

Seasonal Changes in JRC Pavement Deflections

Jointed concrete pavements were not different from asphalt and overlay pavements in that seasonal changes had significant effects on the Dynaflect maximum deflection (DMD) and the S_5 parameter. However, the seasonal variations in the surface curvature index (SCI) and

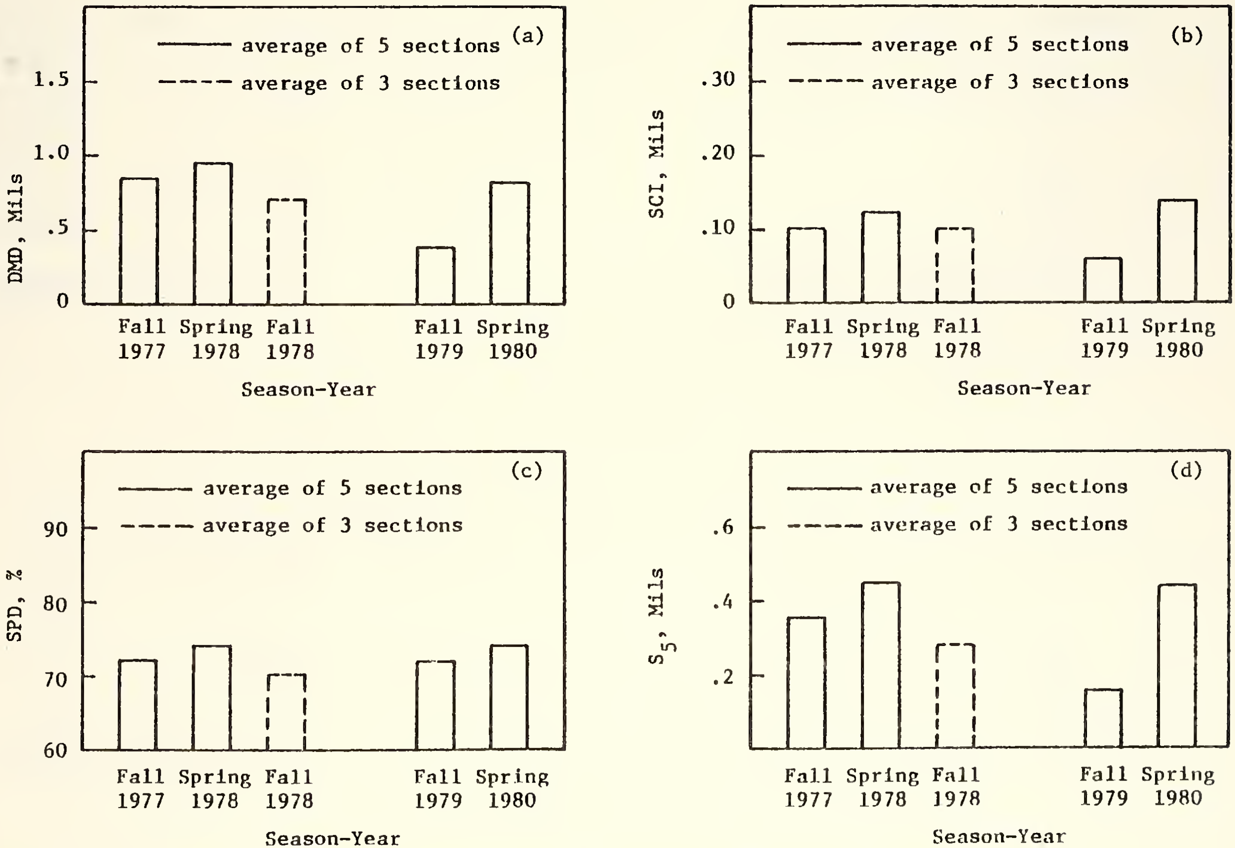

Figure 6.6. Changes in Deflection Parameters of Overlay Pavement Test Sections

TABLE 6.13 . ANOVA- DMD, JRCP SECTIONS

SOURCE	DF	MS	F
S	5	1.442	
ERROR	0	-----	
P	2	0.080	1.1
ERROR *	181	0.076	

S=SECTION , P=POSITION OF TEST
* SP POOLED INTO ERROR TERM

TABLE 6.14. ANOVA- SCI, JRCP SECTIONS

SOURCE	DF	MS	F
S	5	0.858	
ERROR	0	-----	
P	2	0.091	1.4
ERROR *	181	0.065	

S=SECTION , P=POSITION OF TEST
* SP POOLED INTO ERROR TERM

TABLE 6.15 . ANOVA- SPD, JRCP SECTIONS

SOURCE	DF	MS	F
S	5	15359.88	
ERROR	0	--------	
P	2	925.660	< 1
ERROR *	181	1373.373	

S=SECTION , P=POSITION OF TEST
* SP POOLED INTO ERROR TERM

TABLE F6.16. ANOVA- S5, JRCP SECTIONS

SOURCE	DF	MS	F
S	5	0.107	
ERROR	0	-----	
P	2	0.002	< 1
SP	10	0.003	1.5
ERROR	171	0.002	

S=SECTION , P=POSITION OF TEST

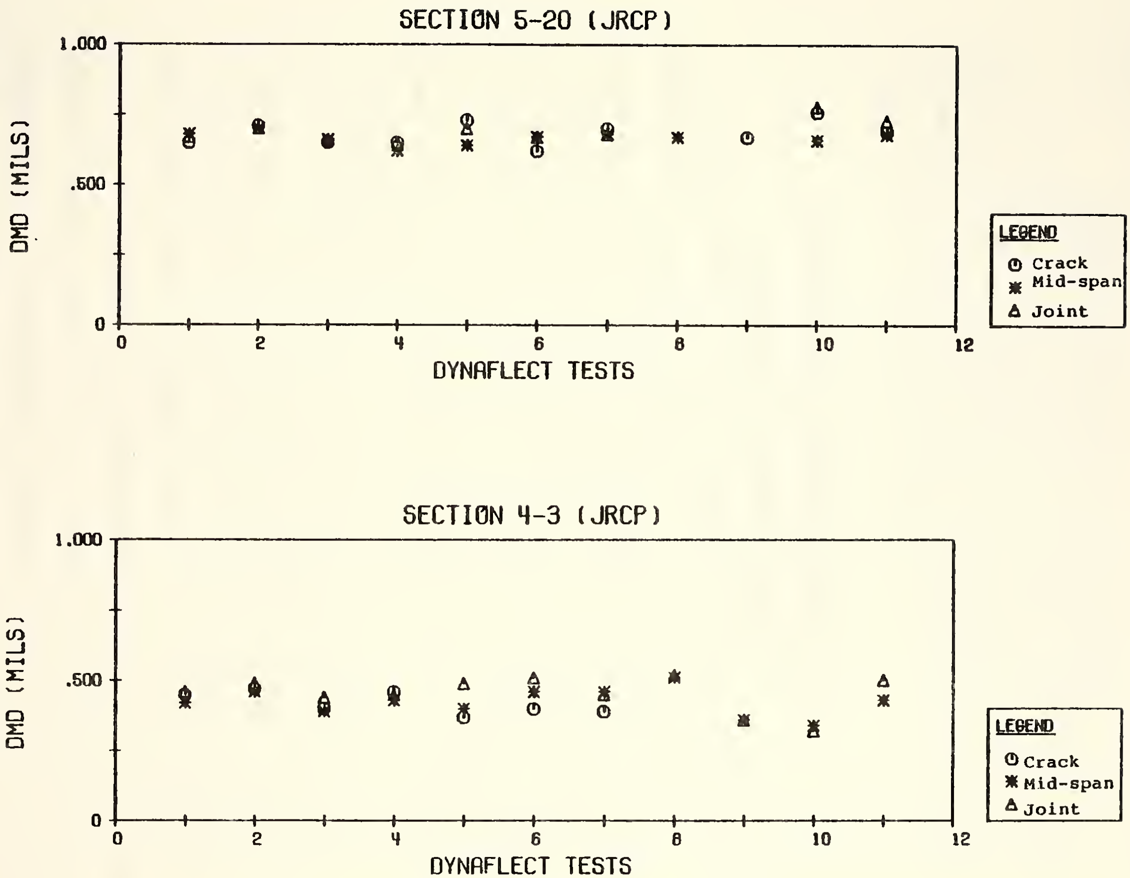

Figure 6.7. Typical Plots of Deflections Measured at the Joint, Crack and Mid-Span Positions on JRC Pavements

spreadability (SPD) were nonsignificant. The analysis of variance is given in Tables 6.17 to 6.20.

Continuously Reinforced Concrete Pavements

In contrast to other pavements, continuously reinforced concrete (CRC) pavements did not experience appreciable changes in their deflections due to seasonal variations as can be seen from the analysis of variance given in Tables 6.21 to 6.24.

Correlations for Predicting Maximum Spring Deflections of Flexible Pavements

In a study conducted in the neighboring states of Illinois and Minnesota, and reported in NCHRP Report No. 76 (51), deflection measurements were made on 24 asphalt pavement test sections to examine the seasonal variations in pavement deflections. The measurements were made on a monthly basis using the Dynaflect equipment. Coverage was given to a wide range of soil, climate and pavement design conditions, and data were collected over almost a full year to include all seasonal variations.

Two areas were selected in each of the two states and six test sections, each 1,000 feet in length, were selected within each area for the testing program. Figure 6.8 shows the locations of the study areas and test sections. Dynaflect measurements were made in the outer wheel path at 100 foot intervals within each of the 1,000 foot sections. Figure 6.9 shows a typical plot of the monthly variations in the measured Dynaflect deflections on an asphalt section. It can be seen that a typical annual deflection history of a pavement subjected to frost action can be divided into four periods:

TABLE 6.17. ANOVA- DMD, JRCP SECTIONS

SOURCE	DF	MS	F
S	5	1.264	
ERROR	0	-----	
T	1	.845	2.5
ST	5	.345	12.3 *
E	1	2.288	6.8 **
SE	5	.338	12.1 *
TE	1	.414	1.1
STE	5	.372	
ERROR	480	.028	

* SIGNIF. AT .01 ** SIGNIF. AT .05
S=SECTION , T=TIME , E=SEASON

TABLE 6.18. ANOVA- SCI, JRCP SECTIONS

SOURCE	DF	MS	F
S	5	.150	
ERROR	0	-----	
T	1	.915	9.4 **
ST	5	.097	6.1 *
E	1	.195	1.7
SE	5	.113	7.1 *
TE	1	.348	4.1
STE	5	.081	
ERROR	480	.016	

* SIGNIF. AT .01 ** SIGNIF. AT .05
S=SECTION , T=TIME , E=SEASON

TABLE 6.19. ANOVA- SPD, JRCP SECTIONS

SOURCE	DF	MS	F
S	5	520.548	
ERROR	0	-------	
T	1	6124.425	16.2 **
ST	5	379.113	8.1 *
E	1	395.997	1.2
SE	5	345.450	7.4 *
TE	1	3029.306	20.3 *
STE	5	149.043	
ERROR	480	46.987	

* SIGNIF. AT .01 ** SIGNIF. AT .05
S=SECTION , T=TIME , E=SEASON

TABLE 6.20. ANOVA- SS READING, JRCP SECTIONS

SOURCE	DF	MS	F
S	5	.212	
ERROR	0	-----	
T	1	1.793	12.9 **
ST	5	.139	46.3 *
E	1	.374	6.8 **
SE	5	.055	18.3 *
TE	1	.182	8.3 **
STE	5	.022	
ERROR	480	.003	

* SIGNIF. AT .01 ** SIGNIF. AT .05
S=SECTION , T=TIME , E=SEASON

TABLE 6.21. ANOVA- DMD, CRCP SECTIONS

SOURCE	DF	MS	F
S	2	1.219	
ERROR	0	-----	
T	1	1.266	253 *
ST	2	.005	< 1
E	1	.330	1.0
SE	2	.324	54.0 *
TE	1	.005	< 1
STE	2	.010	
ERROR	241	.006	

* SIGNIF. AT .01
S=SECTION , T=TIME , E=SEASON

TABLE 6.22. ANOVA- SCI, CRCP SECTIONS

SOURCE	DF	MS	F
S	2	.010	
ERROR	0	-----	
T	1	.039	3.6
ST	2	.011	5.5 *
E	1	.022	3.1
SE	2	.007	3.5 **
TE	1	.018	3.0
STE	2	.006	
ERROR	241	.002	

* SIGNIF. AT .01 ** SIGNIF. AT .05
S=SECTION , T=TIME , E=SEASON

TABLE 6.23. ANOVA- SPD, CRCP SECTIONS

SOURCE	DF	MS	F
S	2	175.976	
ERROR	0	-------	
T	1	403.424	2.8
ST	2	145.529	5.9 *
E	1	61.232	< 1
SE	2	67.572	2.7
TE	1	1094.142	83.5 **
STE	2	13.109	
ERROR	241	24.832	

* SIGNIF. AT .01 ** SIGNIF. AT .05

S=SECTION , T=TIME , E=SEASON

TABLE 6.24. ANOVA- S5 READING, CRCP SECTIONS

SOURCE	DF	MS	F
S	2	.370	
ERROR	0	-----	
T	1	.230	23.0 **
ST	2	.010	10.0 *
E	1	.208	5.9 ***
SE	2	.035	35.0 *
TE	1	.050	16.7 ****
STE	2	.003	
ERROR	241	.001	

*SIG. AT .01 **SIG. AT .05 ***NONSIG.AT .10
**** SIGNIF. AT .10
S=SECTION , T=TIME , E=SEASON

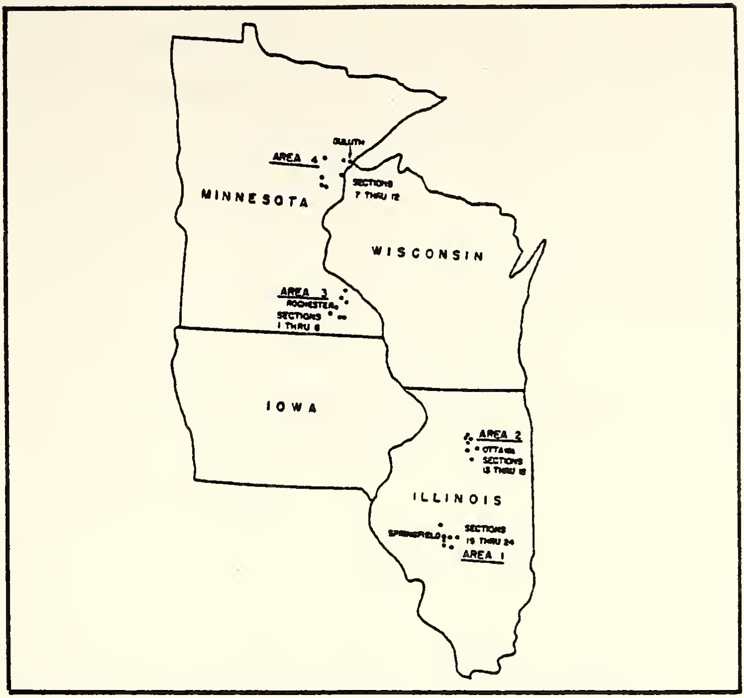

Figure 6.8. Locations of Test Sections (from NCHRP Report No. 76)

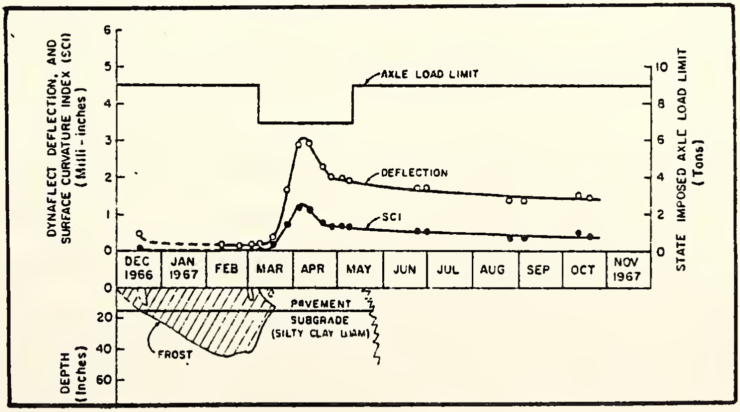

Figure 6.9. Typical Annual Deflection History for An Asphalt Pavement Section (from NCHRP Report No. 76)

i. The period of deep frost when the pavement is strongest.

ii. The period during which the frost is beginning to disappear from the pavement structure. During this period the deflection rises rapidly.

iii. The period of rapid strength recovery. During this period the water from the melting frost leaves the pavement structure and deflection begins to drop.

iv. The period during which the deflection levels off with a general downward trend as the pavement structure continues to slowly dry out.

Regression Analysis and Results

The data provided in the previously mentioned report were studied and analyzed using the computer regression routines available at Purdue as well as the standard statistical techniques (43).

First, regression models were applied to the data collected from areas 1 and 2 (Illinois) on a monthly basis (i.e., a model was developed for each month) using the maximum spring deflection as the dependent variable. The same analysis was made using the data collected from areas 3 and 4 (Minnesota).

The next step was to compare the two regression lines (Illinois vs. Minnesota) for each month. The results showed that the two lines can be pooled together into one line.* In other words, the data collected from both states can be used in one model (for each month). Figures 6.10 and 6.11 show plots of the data and the best fit lines.

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*An example of the statistical test is given in Appendix F.

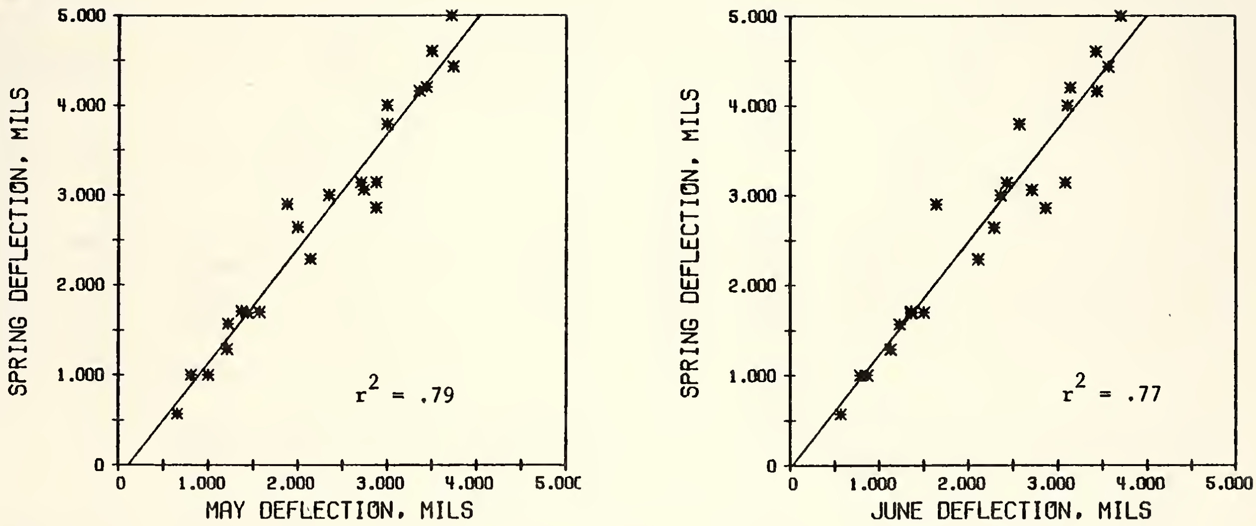

Figure 6.10. Relationship Between Deflections Measured in May and June and the Maximum Spring Deflection (data from NCHRP Report No. 76)

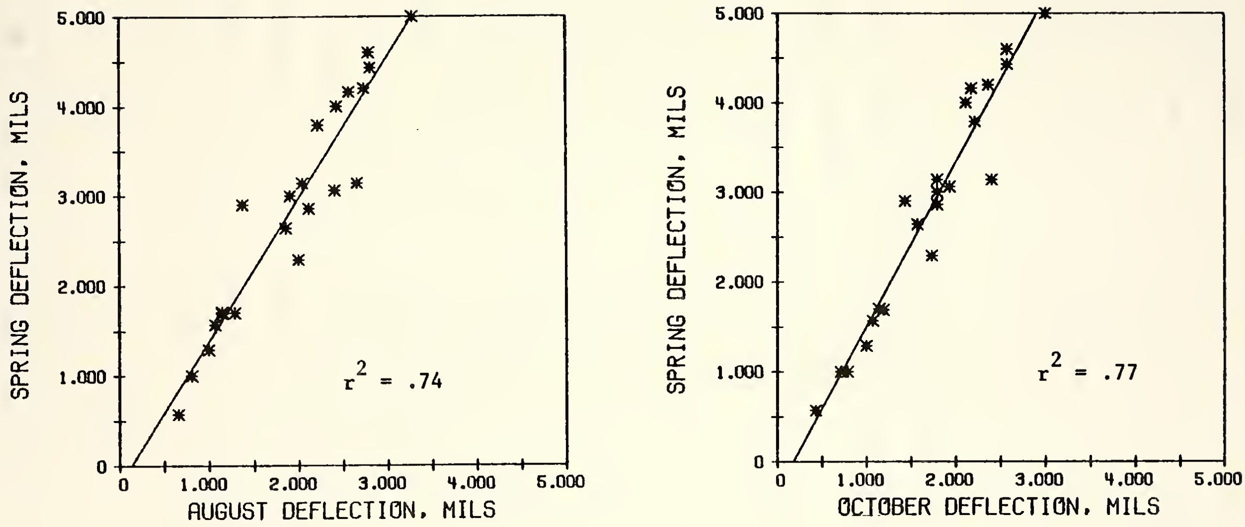

Figure 6.11. Relationship Between Deflections Measured in August and October and the Maximum Spring Deflection (data from NCHRP Report No. 76)

From Figures 6.10 and 6.11 it was noticed that the intercepts of the regression lines were very close to the origins. Consequently, the data were re-analyzed by forcing the regression lines through the origins. Statistical F-test was used to test the mean square error (MSE) for the best fit line against MSE for the regression line through the origin, and it was concluded that the differences were nonsignificant.

Figure 6.12 shows curves that can be used to predict the maximum spring (edge) deflections of asphalt pavements from measurements made during the summer and fall months.

As shown in Figure 6.9, the maximum spring deflections occur during a short period (2-3 weeks) of the year. However, these deflections are the critical ones that must be used in evaluating the structural adequacy of pavements and designing overlays for strengthening pavements. Unfortunately, it is not possible to test a considerable number of highway sections during this short period. The correlations in Figure 6.12, however, provide a means to project the spring deflections for highway sections that cannot be tested in the spring thaw period, from summer and fall measurements. By entering the deflection, measured during a given month, on the horizontal axis and moving vertically to meet the line corresponding to this month (interpolating when needed) and then moving horizontally to read the corresponding maximum spring deflection on the vertical axis.

Summary

In this chapter the various deflection parameters used in evaluating pavement structural adequacy were closely examined for the

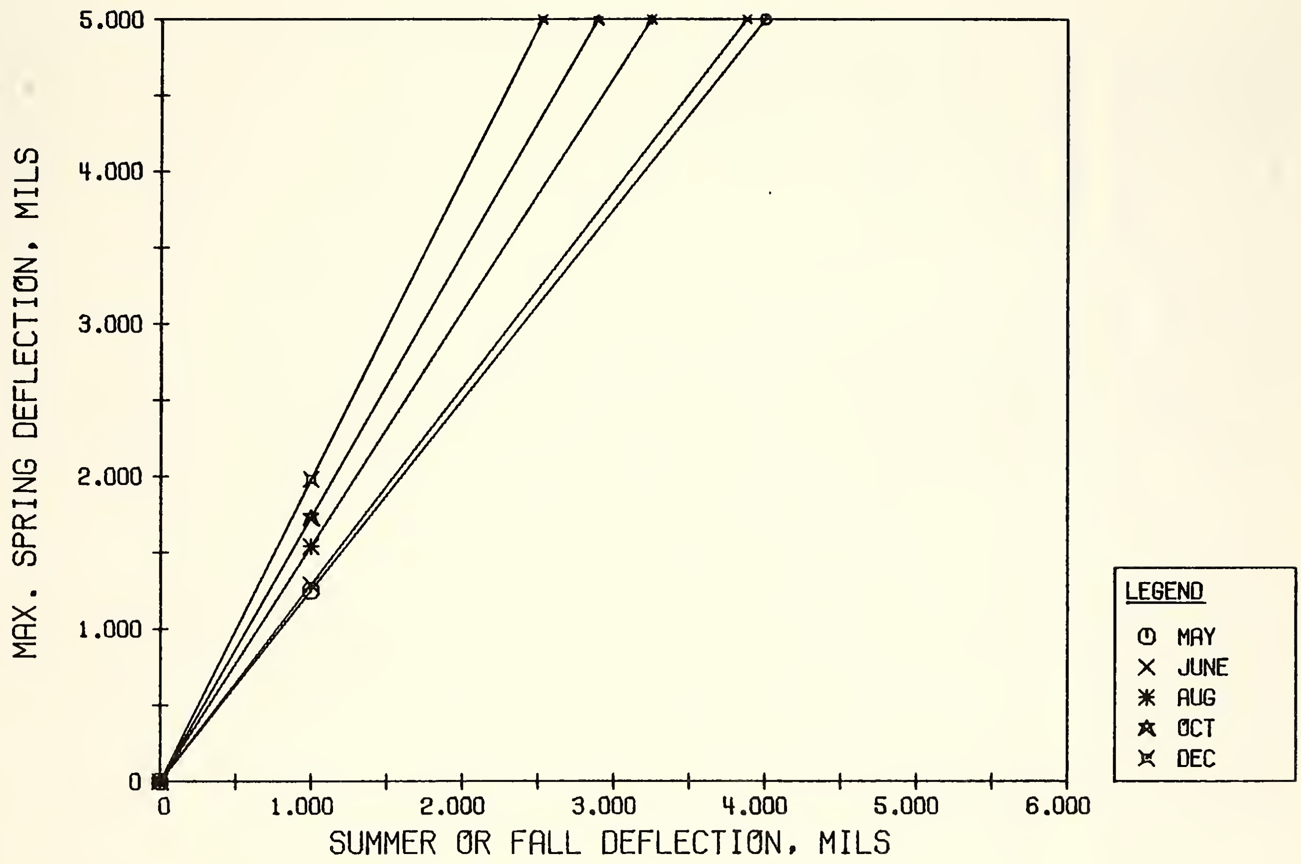

Figure 6.12. Relationship Between Deflections Measured in the Summer and Fall and Maximum Spring Deflection for Asphalt Pavements

four pavement types included in the study. The analysis showed that the deflections of asphalt, overlay and jointed pavements experienced time as well as seasonal changes. The amount of these changes is a function of many factors such as pavement type, design, age, traffic and environmental conditions.

In addition, regression analysis was made for asphalt pavements using data from Illinois and Minnesota and resulted in correlations that can be used for predicting the maximum spring deflections of asphalt pavements from measurements made during the summer and fall months. For flexible pavements, corrections due to temperature variations can be made according to the procedure suggested in reference (4).

CHAPTER 7

CHANGE IN SERVICE LIFE OF OVERLAY AS A FUNCTION OF THE ERROR IN DESIGN DEFLECTION FOR FLEXIBLE PAVEMENTS

In order to arrive at the optimal number of Dynaflect tests, it was considered desirable to examine the relative effects of the error on the pavement's expected service life. Therefore, an investigation was made of the effect of error of estimation on required overlay thickness.

Overlay Design Procedure Adopted in the Investigation

In this investigation use was made of the design procedure developed by the Asphalt Institute (4). This method uses pavement deflections as a basis for designing the asphalt overlays. Figure 7.1 shows the curves used to determine the required overlay thickness depending on the rebound deflection and traffic characteristics of the section under evaluation.

The representative deflection value for the section using the Asphalt Institute's method is equal to the average deflection plus two standard deviations. This value encompasses approximately 98 percent of all deflections measured. The deflection value used for the design is obtained by applying temperature and seasonal factors to the representative deflection.

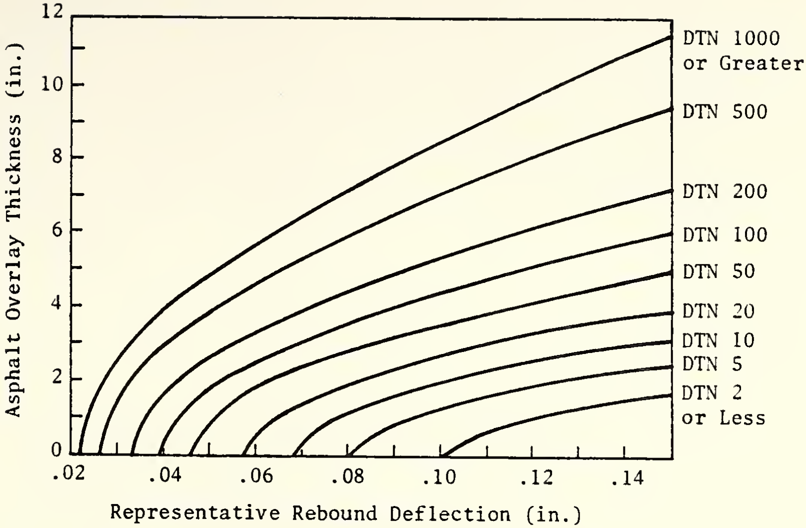

Figure 7.1. Required Overlay Thickness as a Function of Deflection (from Asphalt Institute)

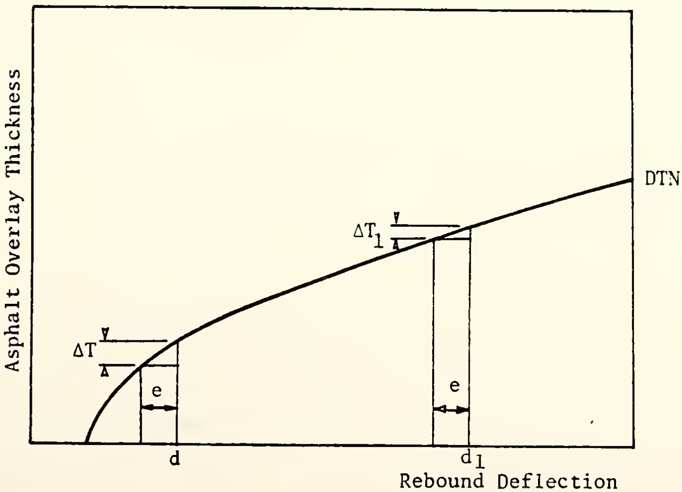

Figure 7.2. Change of Overlay Thickness as a Function of Deflection for a Given Error, e

The curves shown in Figure 7.1 were developed by Kingham (29), who used the equation developed by Kirk (30) based on elastic layered theory. An assumption in the procedure is that the existing pavement and subgrade can be represented by an effective modulus, E_s. This modulus represents the foundation support to the overlay and is derived from the representative rebound deflection by use of the Boussinesq equation, shown in equation

$$d = \frac{1.5\ pa}{E_s} \tag{7.1}$$

where

d = representative pavement deflection (inches)

p = constant pressure (70 psi)

a = radius of single plate (6.4 inches)

E_s = effective modulus

The thickness of overlay required to reduce the representative deflection to a tolerable deflection can then be calculated from Kirk's equation given below

$$L = d\left\{\left(1 - \frac{1}{\sqrt{1+0.8\left(\frac{T}{a}\right)^2}}\right)\frac{E_s}{E_p} + \frac{1}{\sqrt{1+\left(\frac{0.8T}{a}\sqrt[3]{\frac{E_p}{E_s}}\right)^2}}\right\} \tag{7.2}$$

where

L = tolerable pavement deflection (inches)

E_p = overlay modulus (500,000 psi)

T = overlay thickness (inches)

Substituting for L and d, the above equation can be solved for T (overlay thickness). In establishing the magnitude of the tolerable deflection L for various design traffic numbers, DTN*, Kingham selected an intermediate line between the lines suggested by several agencies as shown in Figure 7.3

Effect of Error in Measured Deflection on Overlay Thickness

Equation 7.2 was used for this part of the investigation. A computer program was used to calculate the overlay thickness T using a deflection increment of 0.002 inches and keeping the tolerable deflection L constant (depending on DTN). However, since the deflections in Figure 7.1 are rebound deflections as measured by the Benkelman Beam; use was made of the correlation between the Benkelman Beam and the Dynaflect (51) in order to relate the results to Dynaflect measurements. This correlation takes the following form

$$BB = 20\ DMD \tag{7.3}$$

where

BB = Benkelman Beam Deflection (mils)

DMD = Dynaflect deflection (mils)

Figure 7.2 shows that for a given error, e, in the deflection and for a given DTN the change in the required overlay thickness, ΔT, is a function of deflection (i.e. $\Delta T \neq \Delta T_1$). Also, since the DTN curves are not parallel then the change in the designed overlay thickness, ΔT, due to an error, e, is also a function of DTN.

The error, e, can be either positive or negative, i.e., overestimating or underestimating the correct deflection, respectively.

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*DTN is the design traffic number obtained as the average daily number of 18-kip EAL expected for the design lane during the design period (4).

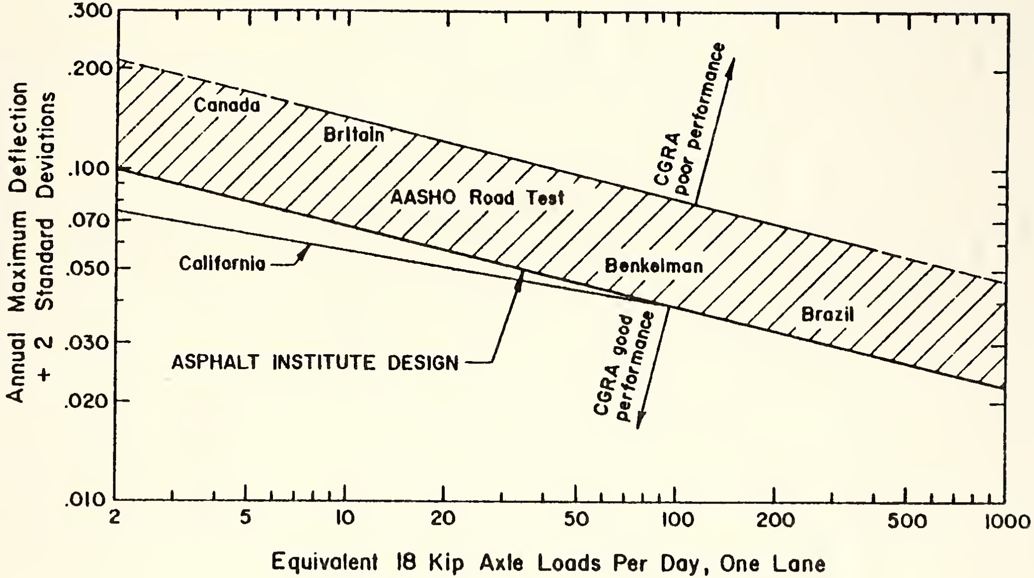


Figure 7.3. Compilation of Beam Deflection Experience (from reference 29)

Overestimating the correct deflection by an error, +e; will result in an increase in the thickness of the overlay by $+\Delta T$, whereas under-estimating the correct deflection by an error, -e; will result in a reduction in the overlay thickness equal to $-\Delta T$.

The effect of the error, e, in the deflection on the change of overlay thickness is depicted in Figures 7.4 to 7.6. Three DTN groups were selected for purposes of illustration - DTN=1000, DTN=200 and DTN=5 representing high, medium and low traffic volumes, respectively. Figures 7.4 to 7.6 also show that the change in overlay thickness is very sensitive to the errors in the deflections near the limiting values. However, this high sensitivity can be overcome by assuming a reasonable minimum overlay thickness for the DTN under consideration. Then, if the measured deflection falls within the range between the limiting deflection and the deflection corresponding to the specified minimum overlay thickness; the minimum thickness is used. The minimum overlay thicknesses assumed for purposes of this investigation were as follows:

DTN	$T_{min.}$ (in.)
1000	4
200	3
5	1

Figures 7.7 and 7.8 show the changes in the designed overlay thickness for the three DTN groups considered at error values of $\pm$ 0.1 mil and $\pm$ 0.2 mil, respectively. The arrows on the curves in Figures 7.7 and 7.8 indicate ΔT at the assumed minimum overlay thickness for each DTN.

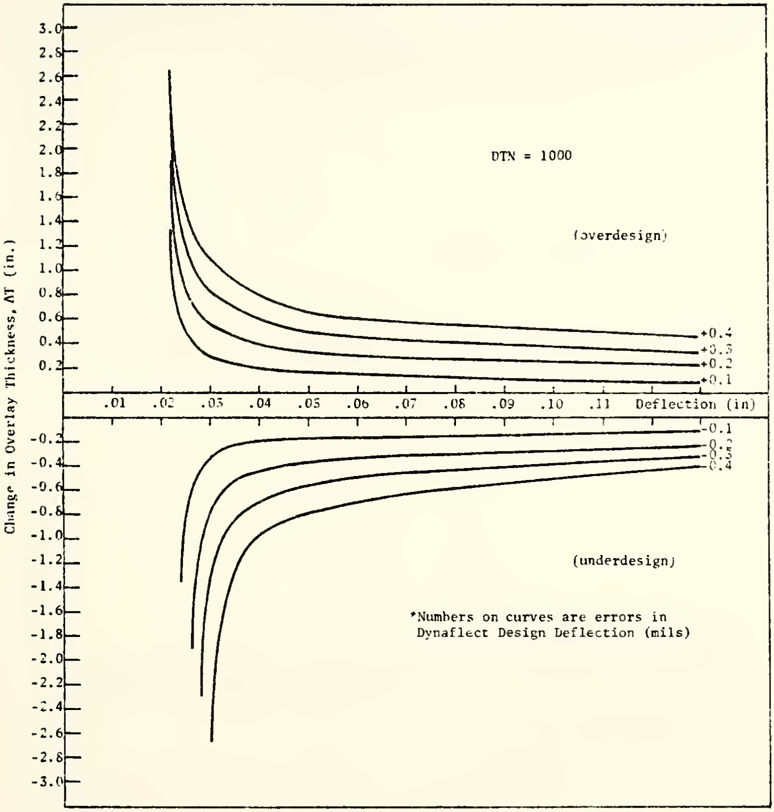


Figure 7.4. Change in Overlay Thickness as a Function of Deflection and Error in Design Deflection (DTN = 1000)

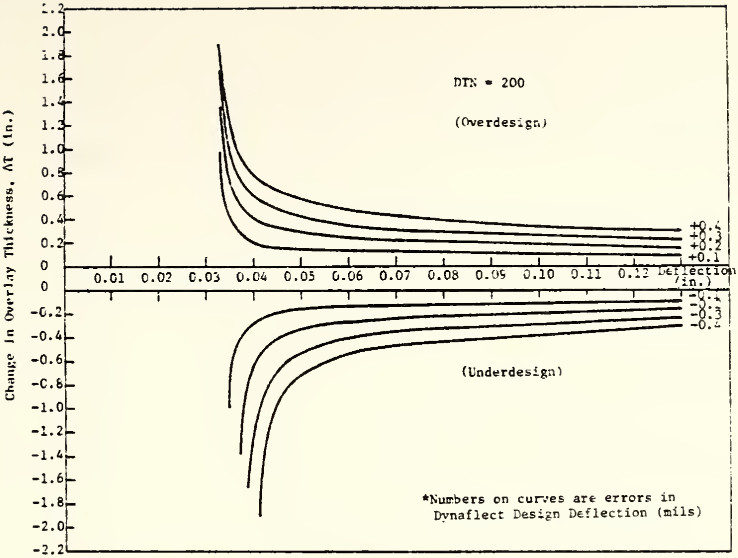


Figure 7.5. Change in Overlay Thickness as a Function of Deflection and Error in Design Deflection (DTN = 200)

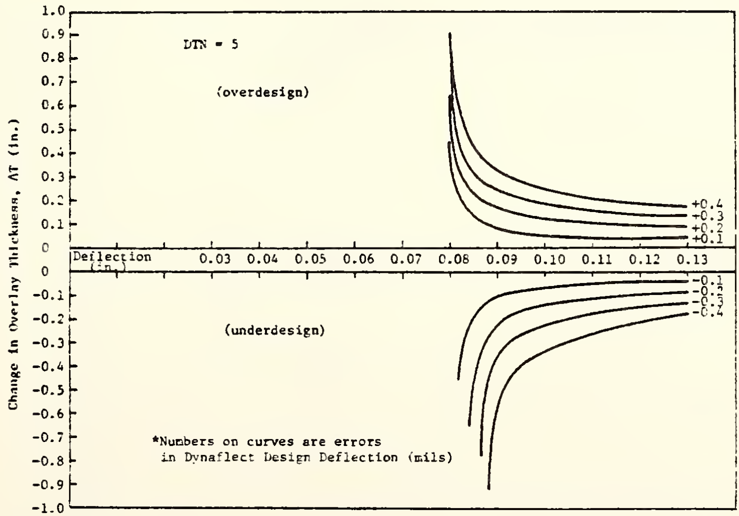


Figure 7.6. Change in Overlay Thickness as a Function of Deflection and Error in Design Deflection (DTN = 5)

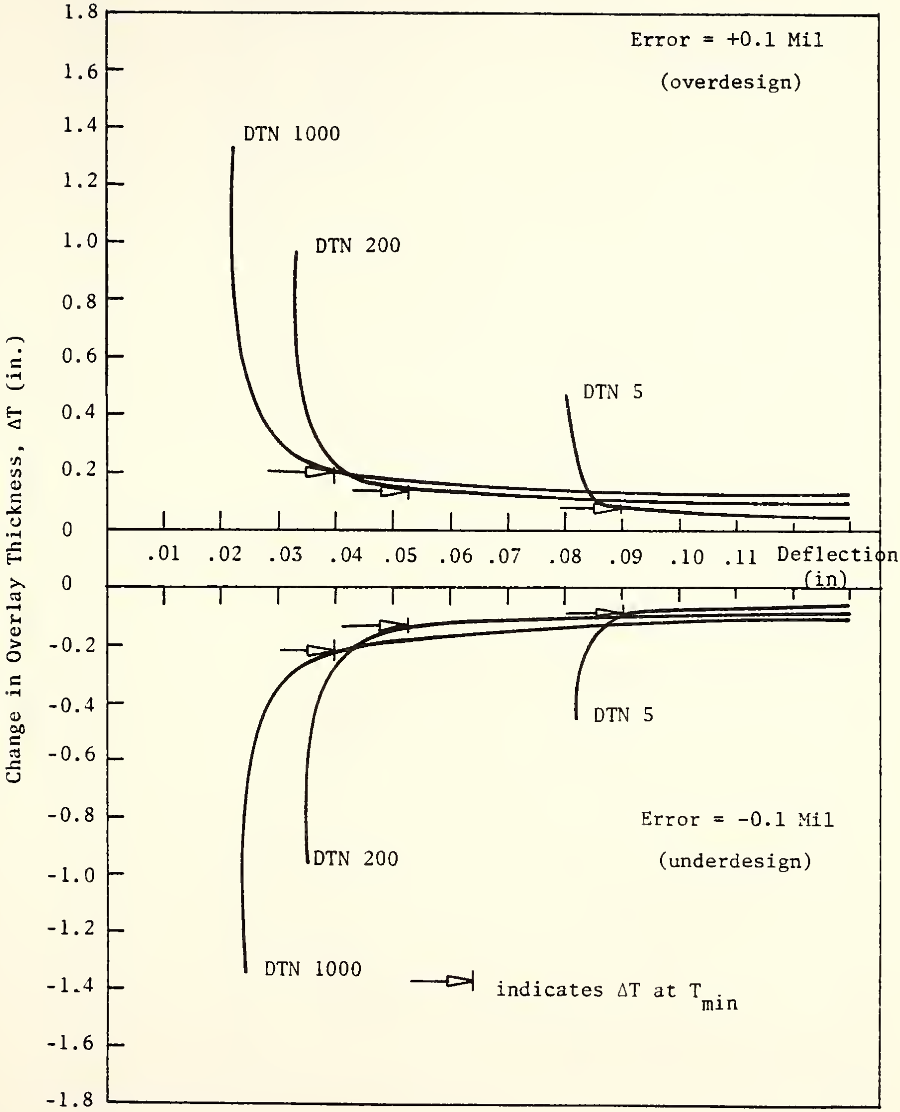


Figure 7.7. Change in Required Overlay Thickness Resulting from an Error of $\pm$ 0.1 Mil Deflection

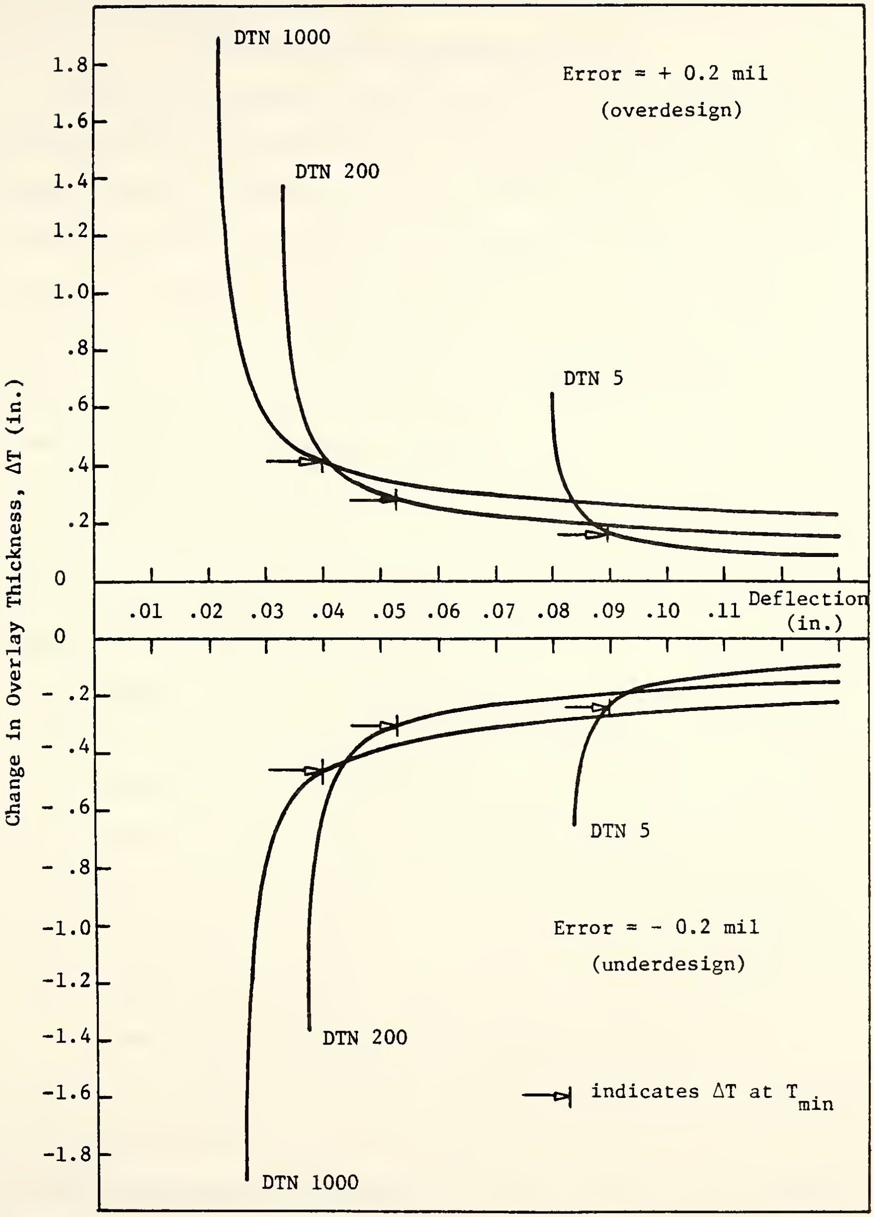


Figure 7.8. Change in Required Overlay Thickness Resulting from an Error of ± 0.2 Mil Deflection

Effect of the Error in Design Deflection on the Service Life of the Designed Overlay

In the above discussion it was shown that for an error, e, in design deflection, there would be a corresponding change in the designed overlay thickness, ΔT. For a negative error (i.e., underestimating the correct deflection), the designed overlay will not be as thick as it should be leading to a reduction in its expected service life. On the other hand, if the error in measurement is positive, the overlay will be overdesigned and, consequently, its actual design service life will be longer.

The concept used for quantifying the effect of the error in deflection on the service life of the resurface is illustrated using Figure 7.9. Assuming that an overlay is to be designed for a given design traffic, DTN, having a limiting deflection, L, and that the actual required thickness is T corresponding to an actual deflection, d, then for an error +e, there will be a corresponding $+\Delta T$. In other words, the situation would be as if the design was for an overlay having a higher design traffic number, DTN_1, as shown in Figure 7.9. The limiting deflection corresponding to DTN_1 is L_1. The same discussion applies for an error, -e, causing the overlay to be underdesigned for a lower design traffic number, DTN_2, having a limiting deflection L_2.

The limiting deflection L_1 can be determined by substituting T_1 ($T_1 = T + \Delta T$) and d in equation 7.2 and solving for L_1. Entering the limiting deflection L_1 on the ordinate in Figure 7.3, the corresponding design traffic number DTN_1 can be read on the abscissa. However, for accurate computational purposes, Figure 7.3 was used to

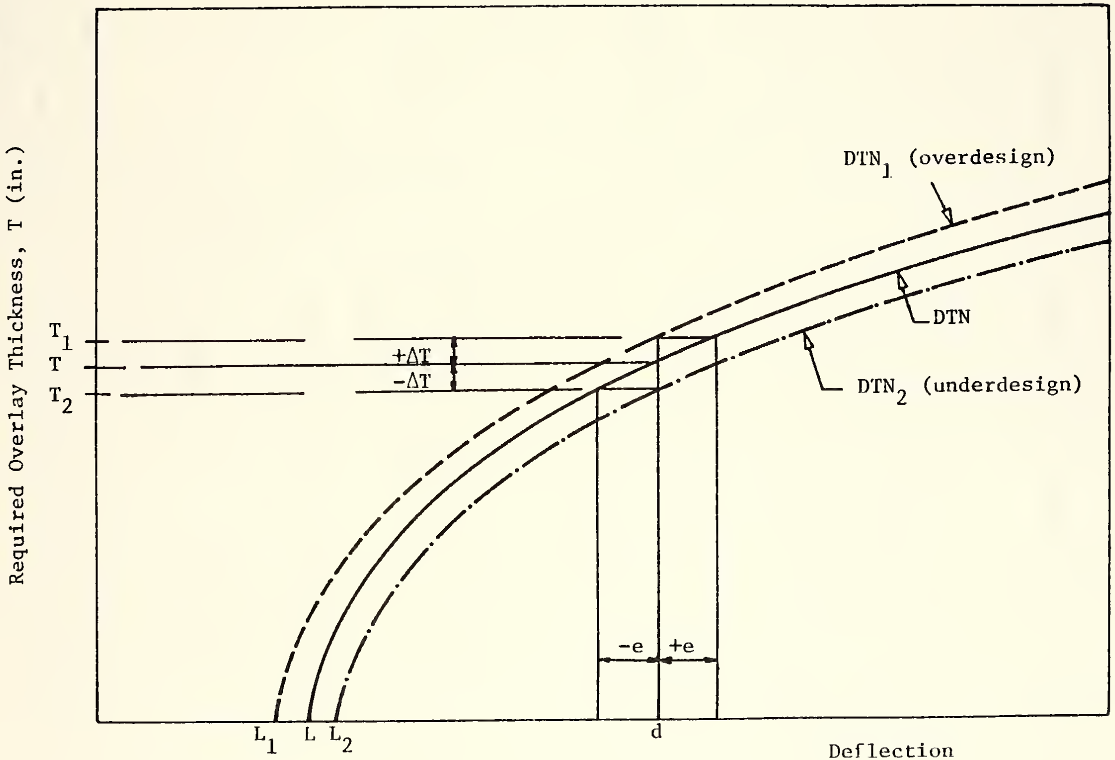


Figure 7.9. Effect of Error, e, in Design Deflection on the Required Overlay Thickness

develop an equation for the line adopted by the Asphalt Institute. This equation takes the following form

$$DTN = 2\left(\frac{0.1}{L}\right)^{4.1} \tag{7.4}$$

where DTN and L are the design traffic number and its limiting deflection, respectively.

Since the calculated DTN is a function of the service life selected for the design, then the service life corresponding to DTN_1 can be obtained and compared to the service life corresponding to DTN (i.e., the design service life). Thus, the change in service life due to an error, e, can be determined.

In the Asphalt Institute method, the design traffic number is determined as follows:

$$DTN = DTN_i \times F \tag{7.5}$$

where

DTN = design traffic number of the analysis period

DTN_i* = initial design traffic number (i.e., at the time the pavement is evaluated)

F = adjustment factor for rate of growth of traffic

$$F = \frac{(1+r)^n - 1}{20r} \tag{7.6}$$

r = annual traffic growth rate

n = design period, years.

A design period, n, of 20 years and an annual growth rate, r, of 4 percent were adopted for this investigation. This gives an F value of 1.49.

*Reference (4) gives a detailed procedure to determine DTN_i.

For each of the three DTN groups (1,000, 200 and 5), the effect of the error in deflection on the service life of the overlay was investigated for each of the curves shown in Figures 7.4 to 7.6 in a range falling between two points (1) point of high ΔT (i.e., at the deflection corresponding to the minimum overlay thickness) as shown by the arrows in Figures 7.7 and 7.8 and (2) point of low ΔT (at a deflection equal to 0.13 inches). The service life can then be calculated using equation 7.6 which can be rewritten as

$$n = \frac{\log(1+20F\ r)}{\log(1+r)} \qquad (7.7)$$

It can be seen from equation 7.5 that a change in DTN will cause a change in F. Notice that DTN_i is constant and can be calculated using the correct design traffic number DTN and F = 1.49 from equation 7.5 as follows

$$DTN_i = \frac{DTN}{1.49} \qquad (7.8)$$

Then it follows that for DTN_1 (as determined from equation 7.4) corresponding to an error, +e:

$$F_1 = \frac{DTN_1}{DTN_i} \qquad (7.9)$$

Calculating F_1 and substituting in equation 7.7, the expected service life resulting from an error +e can be calculated and compared to the correct design life (i.e., 20 years) to determine the change in service life corresponding to this given error.

The results of the analysis are shown in Figure 7.10 which gives the change in service life for each of the DTN groups considered as a function of error in estimating the correct deflection.

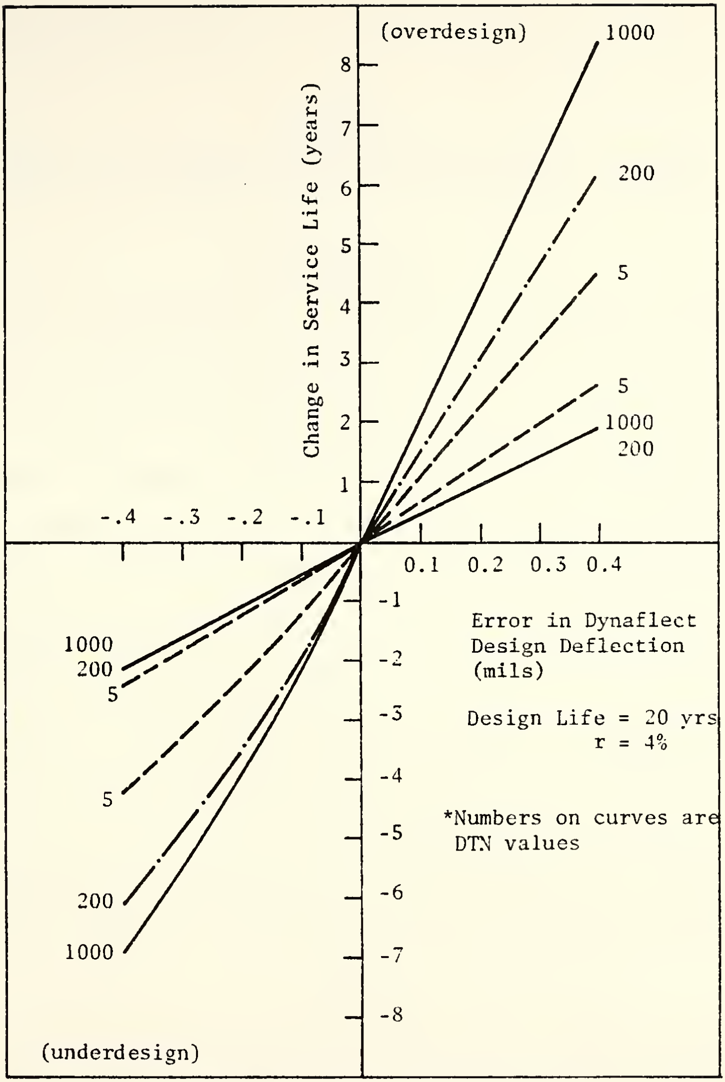


Figure 7.10.Change in Service Life of Resurface as a Function of Error in Dynaflect Design Deflection

CHAPTER 8

VARIABILITY OF PAVEMENT DEFLECTIONS OVER CONTRACT SECTIONS

Study Purpose

While the Dynaflect is a versatile device for assessing pavement structural adequacy and designing overlays, its use requires lane closure which is undesirable especially on high-volume and high-speed highways. Other basic considerations associated with Dynaflect testing relate to the financial, manpower and other resources, plus time, available to do the testing. Therefore, the intensity of measurements; i.e., the number of tests per unit length of road becomes a key factor in Dynaflect testing.

With this in mind, an experiment was designed in order to collect data for the purpose of evaluating the variability of pavement deflections along contract sections as measured by the Dynaflect. The establishment of an understanding of this variability was necessary in order to arrive at the optimal intensity of Dynaflect measurements.

Study Design

It was recognized that the variability of the deflections along contract sections is dependent on pavement type. Therefore, each of the four pavement types included in the study was treated separately in the analysis in order to obtain a typical variability for each pavement type.

Three contract sections were selected, according to a set of guidelines, for each of the four pavement types. Three 1-mile locations were selected within each contract for Dynaflect testing.

Selection of Test Contracts

Use was made of the road inventory prepared by the ISHC Research and Training Center for selecting the test contracts for Dynaflect testing. The selection was made according to the following guidelines:

(1) The contract must have been in service for several years so as to obtain a typical variability of pavement deflections.

(2) Whenever possible test contracts were selected from among those containing the test sections used in the seasonal testing phase so that previous data could be made available if needed.

(3) A minimum contract length of 3.5 miles was selected so that it can accommodate three test locations each 1-mile in length without interference from bridges, ramps, or intersections with other highways.

(4) Uniform traffic conditions along the contract.

(5) As a safety precaution for testing operations, all test sites were required to have adequate sight distance in both directions to provide good visibility for approaching traffic.

(6) It was considered desirable that the contracts be as close as possible to Lafayette in order to reduce travel time and allow more time for testing.

Delineation of Test Locations

A tentative list of contracts suitable for the variability study was prepared. Each contract was then examined in detail using traffic maps, inventory of bridges (28), and the highway inventory prepared by R&TC. Detailed sketches were then prepared for each contract showing a preliminary selection of the 1-mile test locations within each contract relative to contract limits, county lines, bridges and intersections with other highways.

A field survey was next conducted on the selected contracts and the final selection of test locations was made.

In this way a total of 12 contracts were prepared for Dynaflect testing. Appendix G provides the geographic locations of these contracts as well as a summary of the data collected.

Field Data Collection and Procedures

It was considered desirable to obtain a sufficiently large number of Dynaflect measurements on the test contracts in order to have a clearer view of the variability of pavement deflections. However, recognizing that time provisions had to be made for the Dynaflect to travel between the Research & Training Center and the test contracts and also for the placement of the traffic control signs, it was decided that only one contract be tested per day.

All Dynaflect testing operations related to the variability studies were conducted during the months of June and July of 1980.

Testing Asphalt and CRC Pavements

The asphalt and continuously reinforced concrete pavements were tested by the Dynaflect at an intensity of 32 readings for each of the 1-mile locations. The tests were evenly spaced using a measuring wheel which makes measurements to the nearest foot. The tests were made in the outer wheel path of the travel lane (3 feet from pavement edge). At each test station the readings of the 5 sensors were recorded by the Dynaflect operator on the appropriate forms.

Testing Overlay and Jointed Concrete Pavements

The presence of the joints in the jointed concrete pavements and reflection cracks in the overlay pavements required a testing procedure somewhat different from the one used for asphalt and CRC pavements. For the purpose of examining the effects of test position, the tests were made at two positions. For overlay pavements these 2 positions were at a crack and at a good part of the pavement where there were no cracks. For JRC pavements the 2 test positions were at a joint and at a non cracked location of the slab. The Dynaflect tests were made at an intensity of 21 test stations for each of the 1-mile locations within the contracts, testing the previously described two positions each time. Figure 8.1 shows the Dynaflect making a test at a joint position.

Data Analysis

Asphalt Pavements

As previously mentioned three asphalt pavement contracts were randomly sampled and three 1-mile locations were randomly chosen

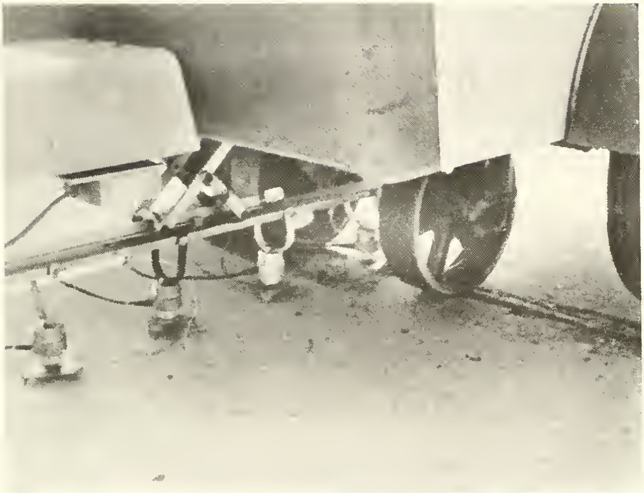


Figure 8.1. Measuring Pavement Deflection at a Joint Position

within each contract. Thirty-two Dynaflect tests were made along each 1-mile location. The analysis of variance model took the following form:

$$Y_{ijk} = \mu + C_i + L_{(i)j} + \varepsilon_{(ij)k} \tag{8.1}$$

$$i=1,2,3 \quad j=1,2,3 \quad k=1,2,\ldots,32$$

where

Y_{ijk} = deflection parameter at the kth test station of the jth location within the ith contract

μ = overall mean

C_i = effect of the ith contract

$L_{(i)j}$ = effect of the jth location within the ith contract

$\varepsilon_{(ij)k}$ = effect of the kth test station in the jth location in the ith contract, random, $NID(0,\sigma^2)$.

Dynaflect Maximum Deflection (DMD)

The results of the analysis of variance on DMD are summarized in Table 8.1. The Burr-Foster Q-Test for homogeneity of variances rejected the hypothesis of equal variances at an α-level of 0.001. Using a square root transformation on the data resulted in homogeneous variances as indicated by the Burr-Foster Q-Test. The analysis of variance (ANOVA) of the transformed data is shown in Table 8.2. However, when the two ANOVA tables were compared, it was noticed that there were no appreciable changes in the values of the F-statistics of the factor effects. In addition, the residual error of the transformed data was too small. Based on this, it was decided to use the ANOVA in Table 8.1 in the analysis.

TABLE 8.1. ANOVA- DMD, ASPHALT SECTIONS

SOURCE	DF	MS	F
C	2	16.376	19.2
L	6	0.854	12.0 *
ERROR	279	0.071	

* SIGNIF. AT .01
C=CONTRACT , L=LOCATION

TABLE 8.2. ANOVA- DMD, ASPHALT SECTIONS(TRNSFD)

SOURCE	DF	MS	F
C	2	3.056	19.7
L	6	0.155	11.9 *
ERROR	279	0.013	

* SIGNIF. AT .01

TABLE 8.3. ANOVA- SCI, ASPHALT SECTIONS

SOURCE	DF	MS	F
C	2	2.784	16.0
L	6	0.174	3.6 *
ERROR	279	0.048	

* SIGNIF. AT .01

TABLE 8.4. ANOVA- BCI, ASPHALT SECTIONS

SOURCE	DF	MS	F
C	2	0.074	2.6
L	6	0.854	9.3 *
ERROR	279	0.003	

* SIGNIF. AT .01

TABLE 8.5. ANOVA- SPD, ASPHALT SECTIONS

SOURCE	DF	MS	F
C	2	831.34	22.0
L	6	37.83	2.0 *
ERROR	279	19.15	

* SIGNIF. AT .10

The F-test for the effects of locations within contracts, as shown by Table 8.1, indicated that location effects on DMD were significant. This result shows that when contracts are tested for deflections, care must be taken in selecting test locations. This is illustrated by the plots shown in Figure 8.2. These plots show the deflections along the one-mile locations within an asphalt pavement contract.

The appropriate deflection testing procedure would then be to distribute the tests along the entire length of the contract, and at the same time make a reasonable number of tests per mile to estimate deflections with an acceptable accuracy.

Deflection Basin Parameters

The various deflection basin parameters -- surface curvature index, SCI, base curvature index, BCI, and spreadability, SPD -- were examined and the following represents a summary of the results.

Surface Curvature Index, SCI - As mentioned earlier, SCI is used as an indicator of pavement stiffness. The analysis of variance (Table 8.3) showed that SCI of asphalt pavements varies significantly from location to location along contract sections. Figure 8.2 shows a plot of SCI values along the 1-mile test locations of contract 2.

Base Curvature Index, BCI - This parameter is indicative of the support conditions underneath the pavement. The analysis (Table 8.4) showed significant variation of BCI along asphalt contracts. Figure 8.3 depicts typical variations of BCI as obtained from field measurements.

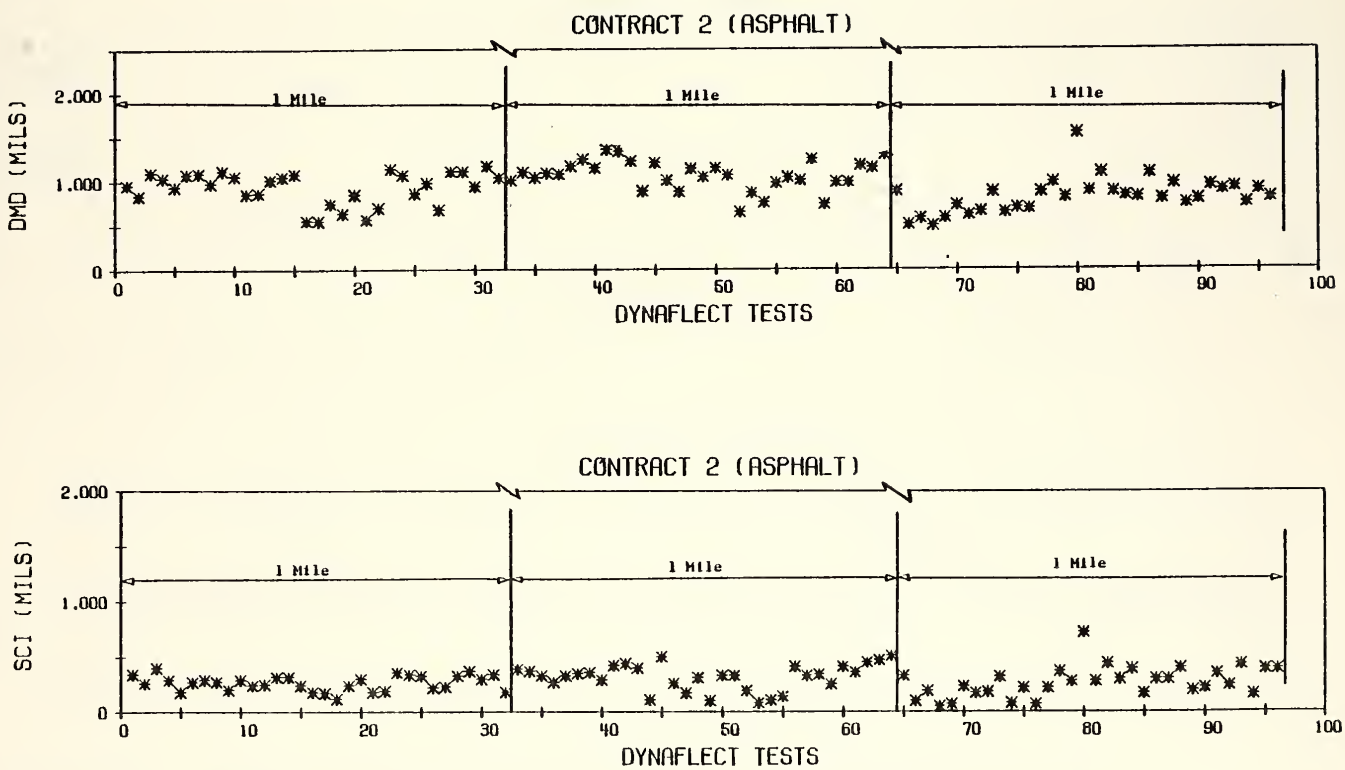


Figure 8.2. Typical Variation of DMD and SCI Along an Asphalt Pavement Contract Section

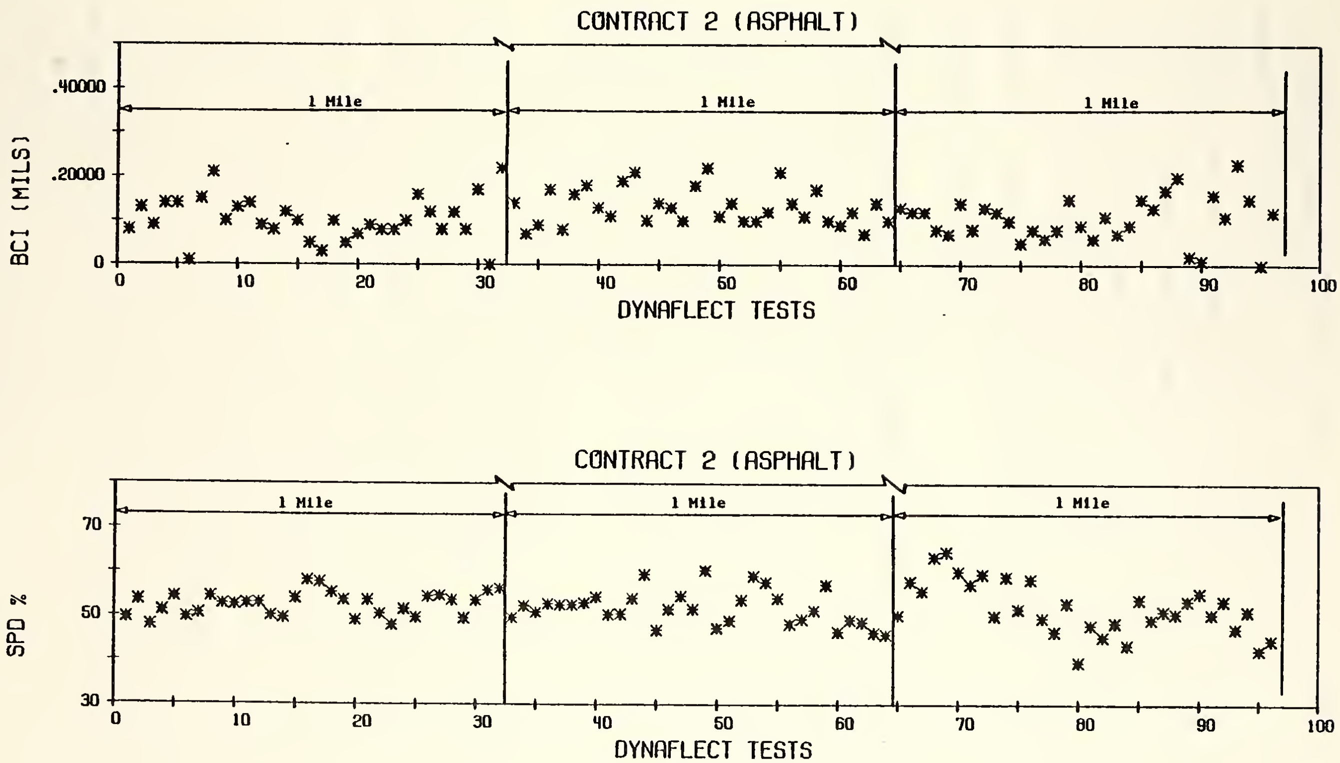


Figure 8.3. Typical Variation of BCI and SPD Along An Asphalt Pavement Contract Section

Spreadability, SPD - This parameter refers to the ability of the pavement to distribute the load on the foundation layers. The variability of SPD was also investigated. The analysis of variance as given in Table 8.5 showed that SPD varies significantly from location to location within the same contract. To obtain a representative SPD value, the measurements have to be distributed along the contract under evaluation. Typical SPD variations along an asphalt contract section are shown in Figure 8.3.

Dynaflect Testing Intensity for Asphalt Pavements

As previously mentioned, the less the number of Dynaflect tests per mile, the less costly and the more efficient testing operations become. However, the accuracy of measurements is an essential factor that cannot be overlooked. Therefore, an investigation of the relationship between the intensity of Dynaflect measurements and the associated accuracy was made.

The overlay design method developed by the Asphalt Institute employs a representative deflection value for the section under evaluation obtained by adding the mean deflection plus 2 standard deviations of the measured deflections for the section. Hence, in order to examine the effect of the number of tests per mile, n, on the error in the estimated representative deflection, a repeated sampling procedure was used in the analysis. The 32 readings were divided into groups having equal numbers of equally spaced test points, n, distributed along the 1-mile test location. For each group, the representative deflection was calculated by adding the mean deflection of the group plus 2 standard deviations. The error in estimating the representative deflection is then the difference between the representative deflection of the group and that obtained from the 32 readings of the particular 1-mile test location. Repeating the above for other locations, several values of the error can be obtained.

Thus, for a given confidence, the error can be estimated depending on the level of n. Figure 8.4 shows the relationship between the number of tests per mile and the error in the representative deflection. This relationship can be used to estimate the error associated with selecting a given number of Dynaflect tests per mile for asphalt pavements.

Referring to Figure 7.10 in Chapter 7, it can be seen that for a given change in the service life of the designed asphalt overlay, the error in estimating the correct representative deflection is a function of DTN (i.e., a function of traffic volumes). For example, for a change in service life equal to -2.5 years, the error for DTN = 1000 is -.12 mils, whereas for DTN = 5, the error is -.23 mils. This means that the tolerable error for low-volume roads is higher than that for high-volume highways.

Figure 8.4 shows that at n = 5 and n = 10, the corresponding errors are $\pm$ 0.23 and $\pm$ 0.13 mils, respectively. Negative values correspond to a reduction in the expected service life of the designed overlay of about -2.5 years for DTN = 5 and -2.7 years for DTN = 1000. These values do not seem appreciable as compared to an overlay design life of 20 years. Also, considering the practical aspects of the Dynaflect field testing operations (i.e., using the tow truck odometer

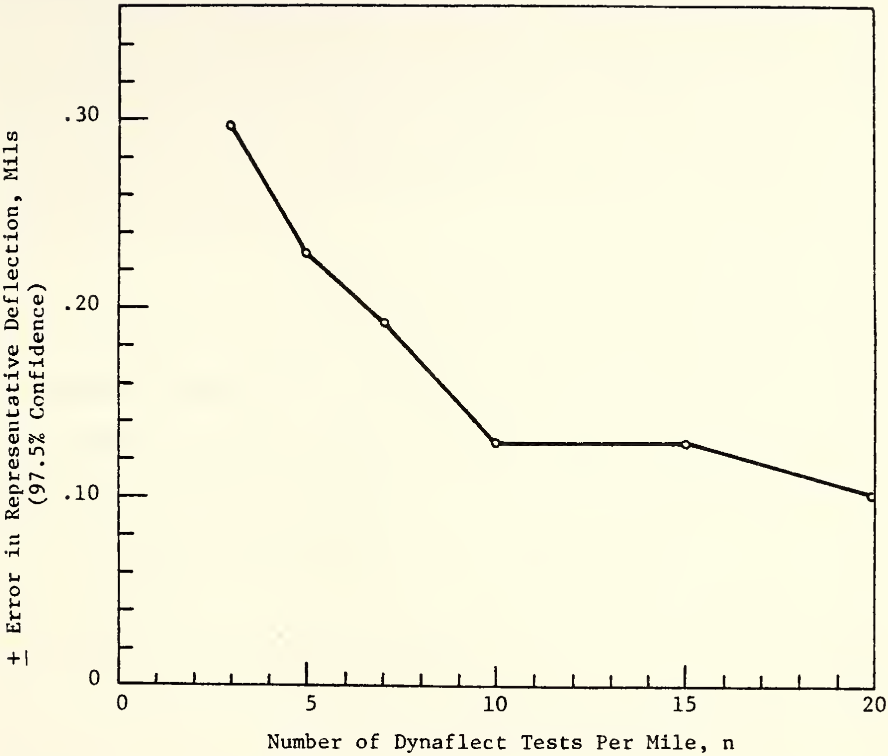


Figure 8.4. Error in Representative Deflection vs. Number of Dynaflect Tests Per Mile (Asphalt Pavements)

to space the tests), a Dynaflect testing intensity of five tests per mile for low-volume roads and ten tests per mile for high-volume roads thus seems reasonable.

Variability analyses were also made to investigate the effect of n = 10 on the error in estimating the other basin parameters. It was shown that this testing intensity is expected to furnish results of reasonable accuracy. A summary of these analyses is provided in Table G2 in Appendix G.

Overlay Pavements

As mentioned earlier, each of the 1-mile locations were tested at a reflection crack and the mid-span of a non cracked position. Twenty-one readings were taken for each position at each 1-mile test location. The model used in the analysis of variance took the following form:

$$Y_{ijk\ell} = \mu + C_i + L_{(i)j} + \delta_{(ij)} + P_k + CP_{ik} + LP_{(i)jk} + \varepsilon_{(ijk)\ell} \tag{8.2}$$

$$i=1,2,3 \quad j=1,2,3 \quad k=1,2 \quad \ell=1,2,\ldots,21$$

where

$Y_{ijk\ell}$ = deflection parameter of the lth test at the kth position in the jth location within the ith contract

μ = overall mean

C_i = effect of the ith contract

$L_{(i)j}$ = effect of the jth location in the ith contract

$\delta_{(ij)}$ = restriction error

P_k = effect of the kth test position

CP_{ik} = effect of the interaction term of the kth position with the ith contract

$LP_{(ij)k}$ = effect of the interaction term of the kth position within the ith contract

$\varepsilon_{(ijk)\ell}$ = within error, $NID(0,\sigma^2)$.

Dynaflect Maximum Deflection, (DMD)

The analysis of variance given in Table 8.6 showed that test position had significant effects on the measured DMD (at α = .10). These effects, however, were nonsignificant at α = .05 level (lower α means higher confidence). From Figure 8.5 it can be seen that at several test stations the mid-span reading was higher than the crack reading. Therefore, it is felt that a good practice would be to take Dynaflect readings at the two positions (crack and mid-span) in order to obtain a good picture of the prevailing deflections.

One-way ANOVA's and Student Newman-Keuls analyses on locations indicated that location effects were significant. This leads to the conclusion that for the conditions of this experiment a clear view can be achieved for the entire contract by distributing measurements over the contract section.

Deflection Basin Parameters

Surface Curvature Index, SCI - The analysis of variance is shown in Table 8.7. The analysis indicated that position of test had no significant effects on SCI (at α = .10). However, the interaction of contract by position was found significant. This result indicates that testing the two positions is the safest way of assessing the

TABLE 8.6. ANOVA- DMD, OVERLAY SECTIONS

SOURCE	DF	MS	F
C	2	4.456	8.7
L	6	0.514	
ERROR	0	-----	
P	1	0.685	12.2 *
CP	2	0.056	2.8
LP	6	0.020	< 1
ERROR	360	0.052	

* SIGNIF. AT .10
C=CONTRACT , L=LOCATION , P=POSITION

TABLE 8.7. ANOVA- SCI, OVERLAY SECTIONS

SOURCE	DF	MS	F
C	2	0.225	1.6
L	6	0.088	
ERROR	0	-----	
P	1	0.371	8.2
CP	2	0.045	7.5 *
LP	6	0.006	< 1
ERROR	360	0.011	

* SIGNIF. AT .05
C=CONTRACT , L=LOCATION , P=POSITION

TABLE 8.8. ANOVA- DCI, OVERLAY SECTIONS

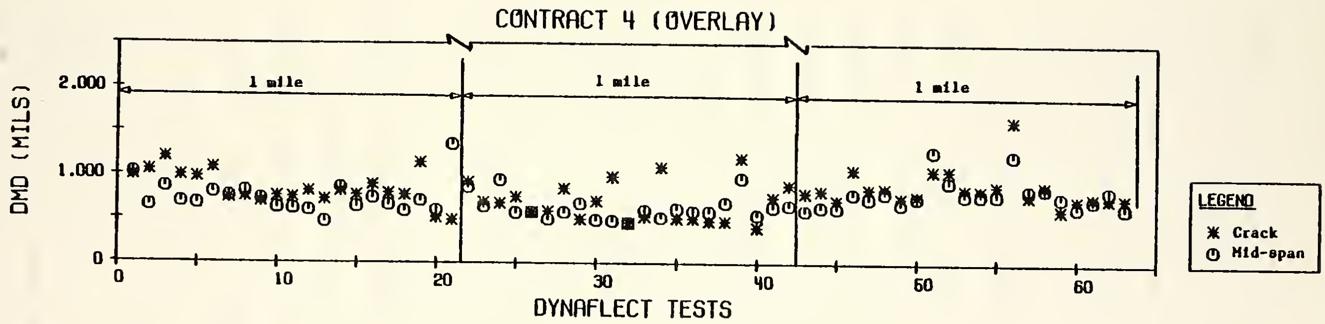
SOURCE	DF	MS	F
C	2	0.197	19.7
L	6	0.010	
ERROR	0	-----	
P	1	0.002	< 1
CP	2	0.006	1.5
LP	6	0.004	< 1
ERROR	360	0.008	

C=CONTRACT , L=LOCATION , P=POSITION

TABLE 8.9. ANOVA- SPD, OVERLAY SECTIONS

SOURCE	DF	MS	F
C	2	432.1	1.6
L	6	278.4	
ERROR	0	-----	
P	1	2523.6	21.6 *
CP	2	117.1	2.7
LP	6	43.1	1.7
ERROR	360	26.1	

* SIGNIF. AT .05
C=CONTRACT , L=LOCATION , P=POSITION



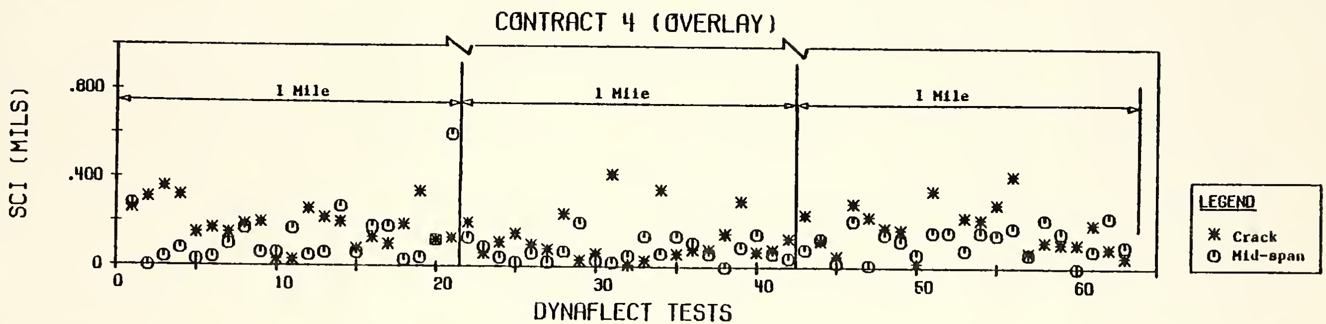


Figure 8.5. Typical Variation of DMD and SCI Along an Overlay Pavement Contract Section

critical SCI values. Figure 8.5 shows plots of typical SCI values along an overlay contract section. One-way ANOVA analyses and Student Newman-Keuls tests showed that location effects were significant, i.e., significant variations in pavement stiffness as measured by SCI existed along contract sections.

Base Curvature Index, BCI - This parameter which indicates support conditions underneath pavements was examined and the analysis showed that in general, BCI did not exhibit significant variations from location to location within a contract section. Also, no significant variations in BCI were found due to position of tests (Table 8.8). Figure 8.6 shows BCI variations along an overlay pavement contract.

Spreadability, SPD - The ability of overlay pavements to distribute the loads, SPD, was found to vary significantly from location to location within a contract section. Also, SPD was found to be dependent on position of test as can be seen from Table 8.9. Figure 8.6 shows typical variations of SPD along an overlay pavement contract section.

Dynaflect Testing Intensity for Overlay Pavements

The approach which was used for investigating the effect of the number of tests on the error in estimating the representative deflection of asphalt pavements was also used for overlay pavements. Since overlay pavements were tested at two positions (crack and mid-span), the error-n relationship was developed for the two positions as shown in Figure 8.7. It can be noticed from Figure 8.7 that the variability of the measurements made at the cracks of overlay pavements is higher than that for the measurements made at the mid-span. In

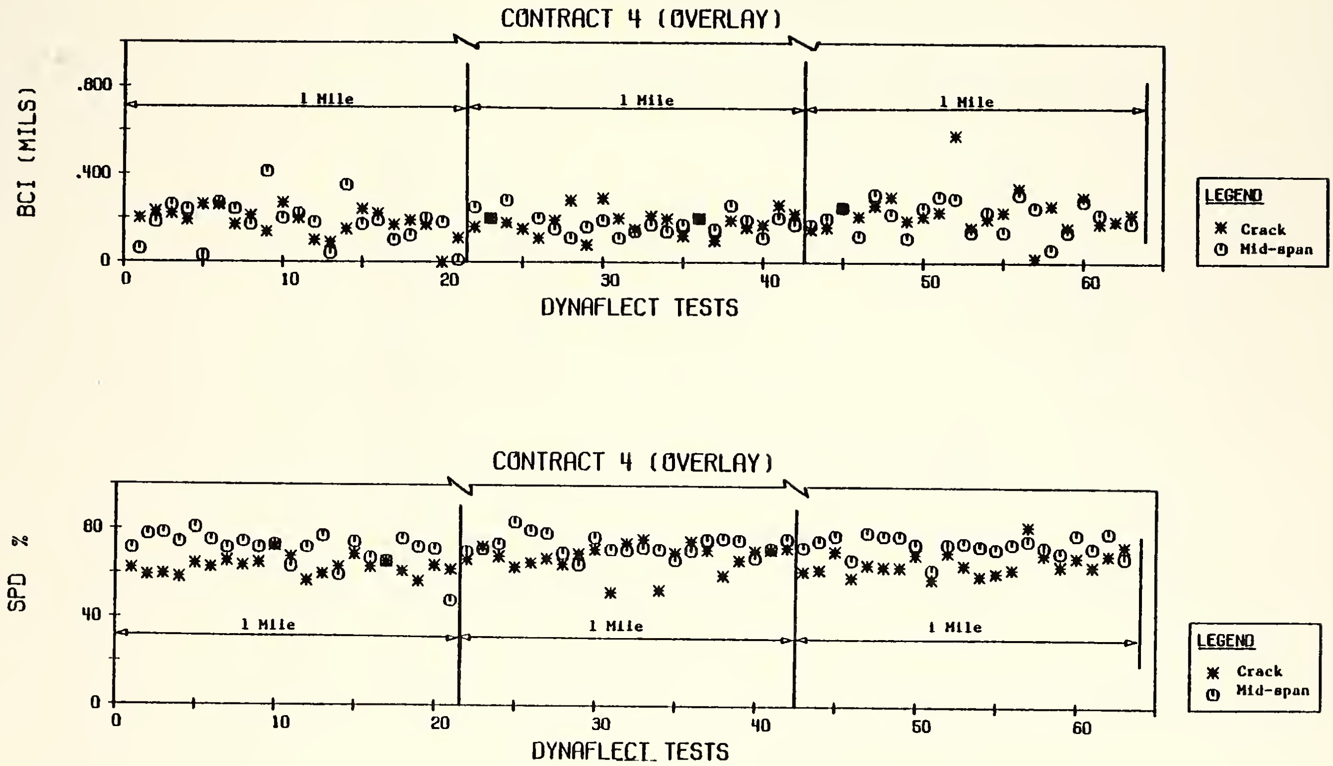


Figure 8.6. Typical Variation of BCI and SPD Along an Overlay Pavement Contract Section

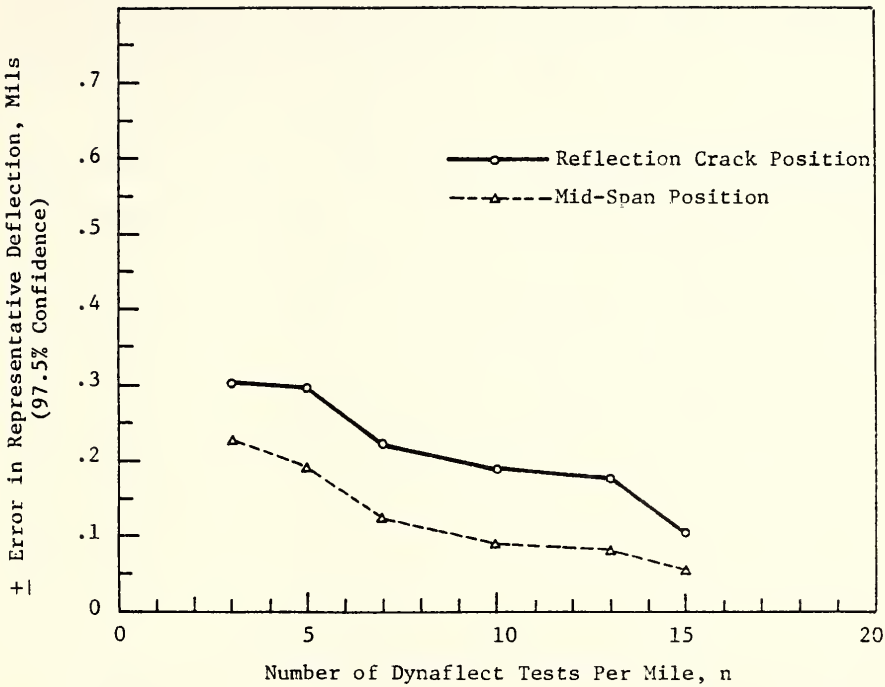


Figure 8.7. Error in Representative Deflection vs. Number of Dynaflect Tests Per Mile (Overlay Pavements)

other words, for a given error in estimating the representative deflection, higher number of tests would be needed for tests made at the crack position of overlay pavements. However, for practical considerations, it would be desirable to take equal number of tests for both positions. This can be done by using the higher variability (crack measurements) for selecting the number of tests.

From Figure 8.7 it can be seen that the error at n = 10 is 0.19 mils (crack position). This amounts to about 13 percent of the overall representative deflection (1.42 mils) as measured at the crack position. For n = 10, the corresponding error for the mid-span position is 0.09 mils, which is about seven percent of the overall representative deflection as measured at the mid-span position (1.22 mils). If these error values are considered reasonable, then the optimal intensity for making Dynaflect measurements on overlay pavements can be taken at ten testing stations per mile. At each station two tests should be made at the two testing positions previously mentioned.

Jointed Reinforced Concrete Pavements

The analysis of variance model used to examine the effects of the factors involved in Dynaflect testing of JRC pavements is the same as model 8.2 used for overlay pavements. The terms remain the same. However, JRC pavements were tested at the joint and at a non cracked part of the slab.

Dynaflect Maximum Deflection, (DMD)

The ANOVA (Table 8.10) showed no significant effects for the position of test at α = .10 which may be attributed to the high value of

TABLE 8.10. ANOVA- DMD, JRCP SECTIONS

SOURCE	DF	MS	F
C	2	0.851	32.7
L	6	0.026	
ERROR	0	-----	
P	1	0.049	< 1
CP	2	0.528	13.2 *
LP	6	0.040	3.3 *
ERROR	360	0.012	

* SIGNIF. AT .01
C=CONTRACT , L=LOCATION , P=POSITION

TABLE 8.11. ANOVA- SCI, JRCP SECTIONS

SOURCE	DF	MS	F
C	2	0.185	61.7
L	6	0.003	
ERROR	0	-----	
P	1	0.176	2.8
CP	2	0.062	10.3 *
LP	6	0.006	2.0
ERROR	360	0.003	

* SIGNIF. AT .05
C=CONTRACT , L=LOCATION , P=POSITION

TABLE 8.12. ANOVA- BCI, JRCP SECTIONS

SOURCE	DF	MS	F
C	2	0.148	29.6
L	6	0.005	
ERROR	0	-----	
P	1	0.003	< 1
CP	2	0.010	2.0
LP	6	0.005	2.5 *
ERROR	360	0.002	

* SIGNIF. AT .05
C=CONTRACT , L=LOCATION , P=POSITION

TABLE 8.13. ANOVA- SPD, JRCP SECTIONS

SOURCE	DF	MS	F
C	2	653.8	9.7
L	6	67.4	
ERROR	0	-----	
P	1	4562.0	7.8
CP	2	587.0	19.0 *
LP	6	30.9	1.8
ERROR	360	17.7	

* SIGNIF. AT .01
C=CONTRACT , L=LOCATION , P=POSITION

position by contract interaction. Separate analyses on contracts showed that test position can have significant effects on variations of DMD measurements along JRC contract sections. The interaction terms (position by contract and position by location) were found significant indicating that in order to avoid inherent performance differences from contract to contract and from location to location within the same contract, the tests should be made at the two positions and distributed along the length of the contract under evaluation.

Figure 8.8 shows a typical plot of the variations of measured deflections along a JRC pavement contract section for the two test positions.

Deflection Basin Parameters

Surface Curvature Index, SCI - The variation of SCI was examined and the ANOVA (Table 8.11) showed the same result obtained above that the position of tests has nonsignificant effects on the variation of SCI. Separate analyses on individual contracts were made to examine SCI variations. It was found that position of test can be significant and that locations can have pronounced effects on measured SCI values. Figure 8.8 shows SCI variations along a JRC contract for the two testing positions.

Base Curvature Index, BCI - The analysis of variance corresponding to evaluating BCI variations along JRCP contracts relative to location and position of test is shown in Table 8.12. Analyses on individual contracts indicated that variation of BCI, similar to DMD and SCI, can be affected by location and by position of test. Figure 8.9 depicts BCI variations along a JRC pavement test contract.

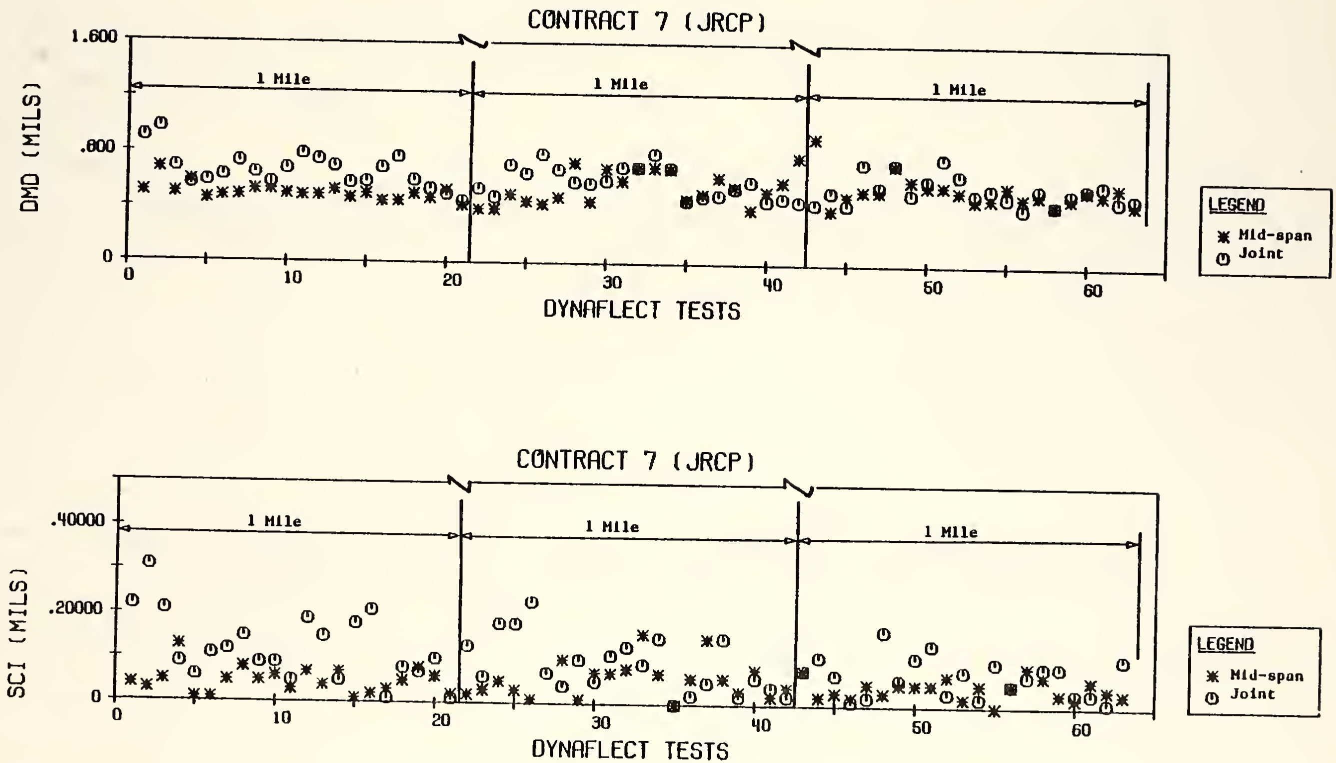
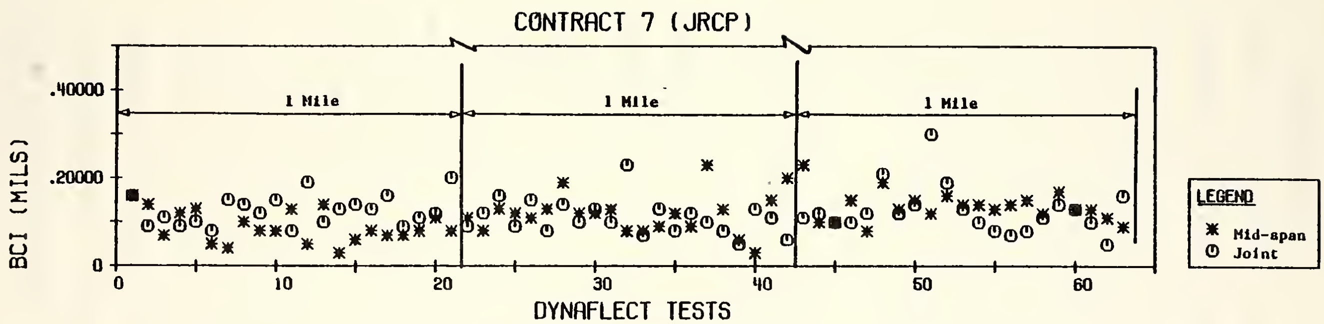


Figure 8.8. Typical Variation of DMD and SCI Along a JRC Pavement Contract Section



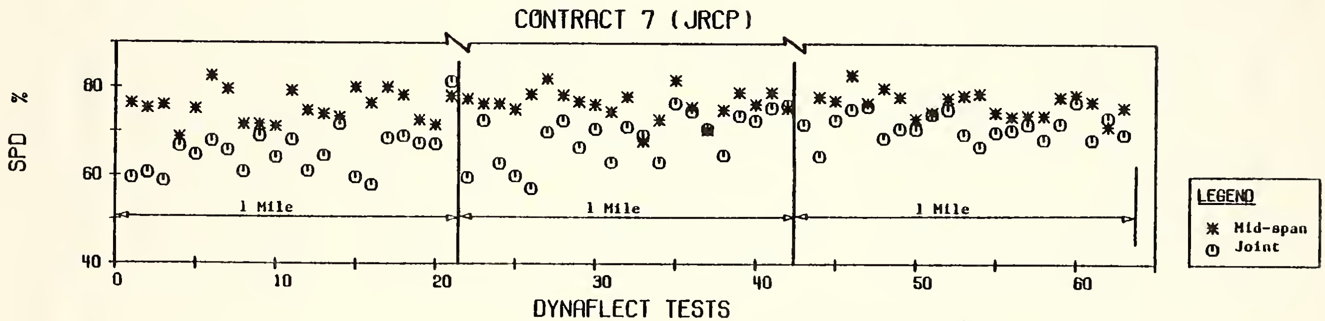


Figure 8.9. Typical Variation of BCI and SPD Along a JRC Pavement Contract Section

Spreadability, SPD - The variability of the ability of JRC pavement to distribute the loads on the foundation layers as expressed by spreadability, SPD, was examined (Table 8.13). Similar to the other basin parameters, factors affecting SPD variations exhibited similar features leading to the conclusion that accurate assessment of this particular parameter along a given contract requires testing both positions on the slab (joint and mid-span) and at the same time distributing the measurements on the length of the contract under evaluation. Figure 8.9 shows the variations of SPD along a JRCP contract.

Dynaflect Testing Intensity for JRC Pavements

Figure 8.10 shows the relationship between the number of Dynaflect tests and the corresponding error in the representative deflection for each of the two testing positions (joint and mid-span). The variability of the deflections measured at the joint is shown to be slightly higher than that for the deflections measured at the mid-span position. As for overlay pavements, it would be more practical to select an equal number of tests for both testing positions. This can be achieved by using the variability associated with the joint position since it is the higher one.

From Figure 8.10, the error in estimating the representative deflection at the joint position for n = 10 is shown to be about 0.06 mils, which represents seven percent of the overall representative deflection as measured at the joints (.847 mils). Based on this, it can be stated that a Dynaflect testing intensity of ten test stations per mile seems appropriate. At each test station, two Dynaflect

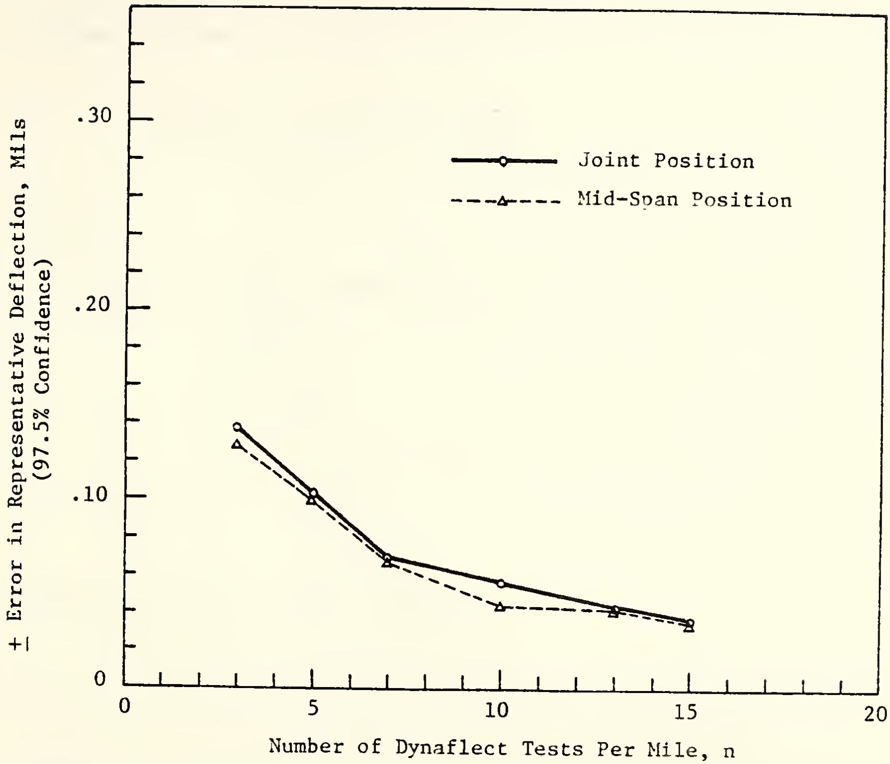


Figure 8.10. Error in Representative Deflection vs. Number of Dynaflect Tests Per Mile (JRC Pavements)

readings should be taken one at a joint and another one at a mid-span position.

Continuously Reinforced Concrete Pavements

The model employed in examining deflection variations for CRC pavements assumed the following form:

$$Y_{ijk} = \mu + C_i + L_{(i)j} + \varepsilon_{ijk} \tag{8.3}$$

$$i=1,2,3 \quad j=1,2,3 \quad k=1,2,\ldots,29$$

where

Y_{ijk} = deflection parameter measured at the kth station in the jth location within the ith contract

μ = overall mean

C_i = effect of the ith contract

L_{ij} = effect of the jth location in the ith contract

ε_{ijk} = error, $NID(0,\sigma^2)$.

Dynaflect Maximum Deflection (DMD)

The statistical analysis of variance is summarized in Table 8.14. The test for location effects indicated that pavement deflections can vary significantly from location to location within a CRC pavement contract. Figure 8.11 shows typical deflection variations along a CRC contract.

These results indicate that in order to conduct a meaningful evaluation of CRC pavement deflections the tests have to be made on all the contract under evaluation. In other words, sampling a short stretch of a contract is not a good practice to make appropriate inferences regarding structural adequacy.

TABLE 8.14. ANOVA- DMD, CRCP SECTIONS

SOURCE	DF	MS	F
C	2	0.028	< 1
L	6	0.049	4.9 *
ERROR	252	0.010	

* SIGNIF. AT .01
C=CONTRACT , L=LOCATION

TABLE 8.15. ANOVA- SCI, CRCP SECTIONS

SOURCE	DF	MS	F
C	2	0.068	22.7
L	6	0.003	1.5
ERROR	252	0.002	

TABLE 8.16. ANOVA- BCI, CRCP SECTIONS

SOURCE	DF	MS	F
C	2	0.097	7.5
L	6	0.013	6.5 *
ERROR	252	0.002	

* SIGNIF. AT .01

TABLE 8.17. ANOVA- SPD, CRCP SECTIONS

SOURCE	DF	MS	F
C	2	22.2	< 1
L	6	46.5	1.5
ERROR	252	31.5	

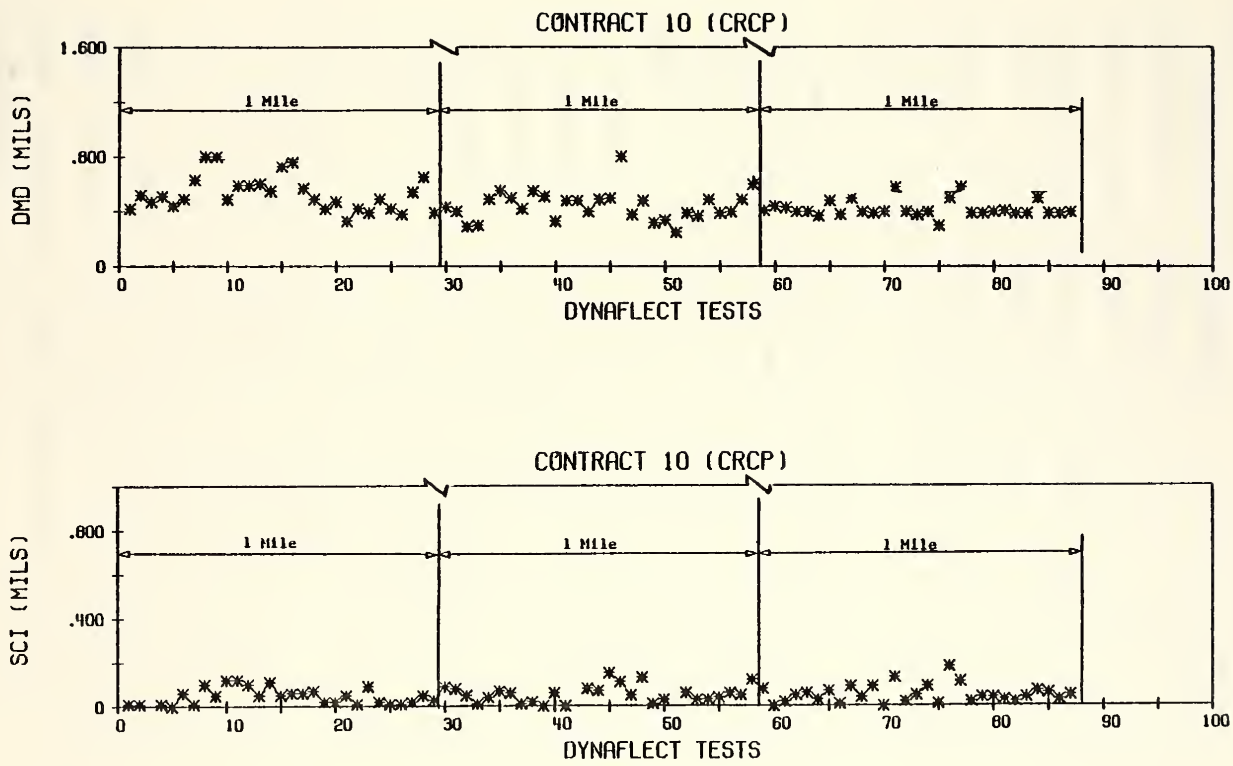


Figure 8.11. Typical Variation of DMD and SCI Along a CRC Pavement Contract Section

Dynaflect Basin Parameters

Surface Curvature Index, SCI - Variation in pavement stiffness, as indicated by SCI, along CRCP contracts was examined. The analysis (Table 8.15) showed that CRC pavements did not exhibit significant variations in SCI along contract sections. Among the 4 pavement types considered in this research CRC pavements only exhibited this characteristic of uniform stiffness from location to location within a contract. Figure 8.11 depicts the variations in SCI along a CRC contract section.

Base Curvature Index, BCI - This parameter was examined using the ANOVA in Table 8.16. The results of the analysis indicated that pavement support conditions, as evaluated by BCI, under CRC pavements vary significantly from location to location along a given contract. A typical example of this variation is shown in Figure 8.12.

Spreadability, SPD - The variability of SPD (ability of pavement to distribute the loads) along CRC highway contracts was studied. The results (Table 8.17) indicated that the variations in SPD from location to location in a given contract were non-significant. Figure 8.12 presents a typical plot of SPD variability along a highway section.

Dynaflect Testing Intensity for CRC Pavements

The error - n relationship for CRC pavements is shown in Figure 8.13. It is quite noticeable that the error in estimating the representative deflection decreases rapidly with the increase in the number of tests, n, until a value of n = 9 is reached where the error starts to experience a lower reduction rate with respect to the increase in n.

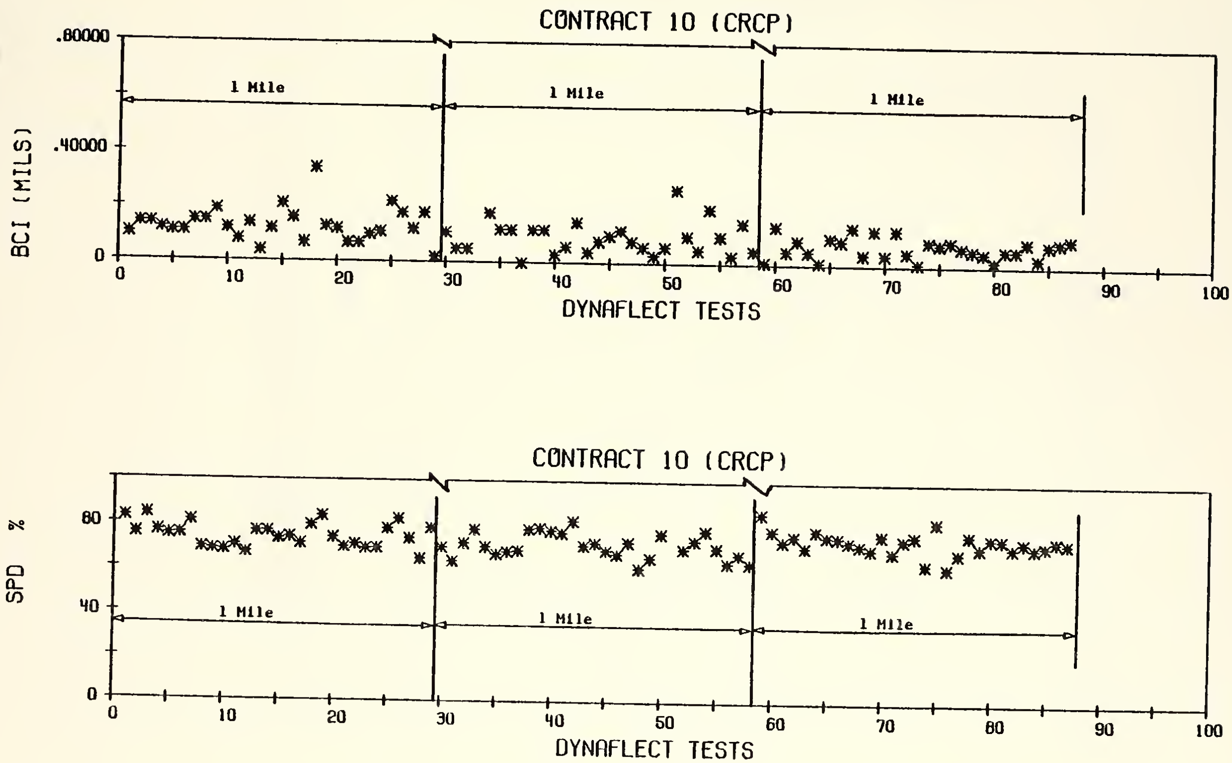


Figure 8.12. Typical Variation of BCI and SPD Along a CRC Pavement Contract Section

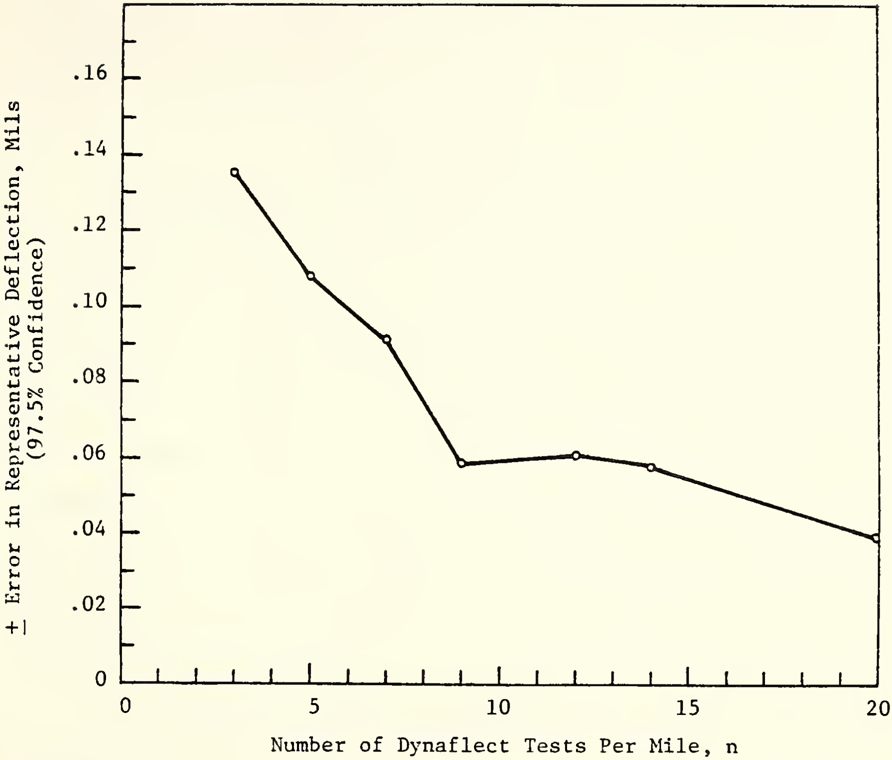


Figure 8.13. Error in Representative Deflection vs. Number of Dynaflect Tests Per Mile (CRC Pavements)

The relationship given in Figure 8.13 shows that for n = 10 tests per mile, the corresponding error in measuring the representative deflection for CRC pavements is 0.06 mils which is about 9 percent of the overall representative deflection (0.67 mils) which seems a reasonable value for practical purposes. Thus, a Dynaflect testing intensity of ten readings per mile seems adequate.

Summary of Results

The objective of the variability study of pavement deflections was to study the variations of pavement deflections for each pavement type included in the research along highway contract sections in order to develop an understanding of the nature of these variations. For many reasons discussed in previous paragraphs, it appears desirable to use highway contract sections as evaluation units. Therefore, the primary objective of this portion of the study was to determine the most efficient procedure for evaluating pavement structural adequacy using deflection measurements along the evaluation units, i.e. contract sections.

The following is a brief summary of the results of the deflection variability study:

1 - Variability of Deflections Along Contract Sections

The analysis showed that the variation of the measured deflection parameters between the different 1-mile locations within a contract section was statistically significant for all the pavements included in the study (except for SCI and SPD of CRCP and BCI of overlay pavements). Therefore, sampling a short stretch within a contract is not expected to provide representative values. The optimum procedure for making the Dynaflect measurements requires that the tests be distributed along the length of the contract under evaluation.

The presence of joints in JRC pavements and reflection cracks in overlay pavements requires that the tests be made at two positions at each test station. Overlay pavements should be tested at a reflection crack and at a mid-span position (i.e. a good area where there is no cracking). Jointed concrete pavements should be tested at a joint position and at a mid-span position.

2 - Dynaflect Testing Intensity

The analysis of the effect of using varying numbers of Dynaflect tests per mile on the error in estimating the representative deflection showed that for low-volume flexible pavements an intensity of five tests per mile is expected to provide representative results with reasonable accuracy. For high-volume flexible pavements as well as all concrete and overlay pavements, an intensity of ten test stations per mile seems to be adequate to furnish representative values of reasonable accuracy. However, overlay and JRC pavements should be tested at two positions at each testing station as described above. The representative deflection would then be calculated from the average plus two standard deviations of these 20 readings.

Contracts on two-lane high-volume highways need to be tested in both directions of travel, thereby obtaining two deflection profiles for the highway. The measurements should be staggered so as to obtain a better coverage of the highway. The representative deflection of the highway would then be calculated from the combined readings of the two profiles.

CHAPTER 9

OUTLINE OF A COMPREHENSIVE PAVEMENT EVALUATION SYSTEM

A comprehensive evaluation system serves two basic purposes:

1) It provides the decision makers with specific and objective information on the present status and rehabilitation needs of the pavements within the highway network as determined by performing a set of measurements utilizing specific equipment and according to systematic techniques.

2) It provides a continuous feedback system for updating the information on the condition of pavement sections. This allows establishing performance trends for individual sections which can later, when the system is fully operational, be used for assessing future needs.

As mentioned earlier, there are four basic components of a comprehensive pavement evaluation system: (1) pavement properties that can be measured and used as indicators of its condition and performance with time, (2) equipment to make pavement properties' measurements, (3) systematic techniques for collecting the data and (4) efficient and continuous feedback systems.

Figure 9.1 shows a framework for a comprehensive pavement evaluation system that serves as a tool for providing the top management with data collected at the project level, but suitable for making decisions at the network level. As outlined in Figure 9.1, the various phases involved in the evaluation process are as follows:

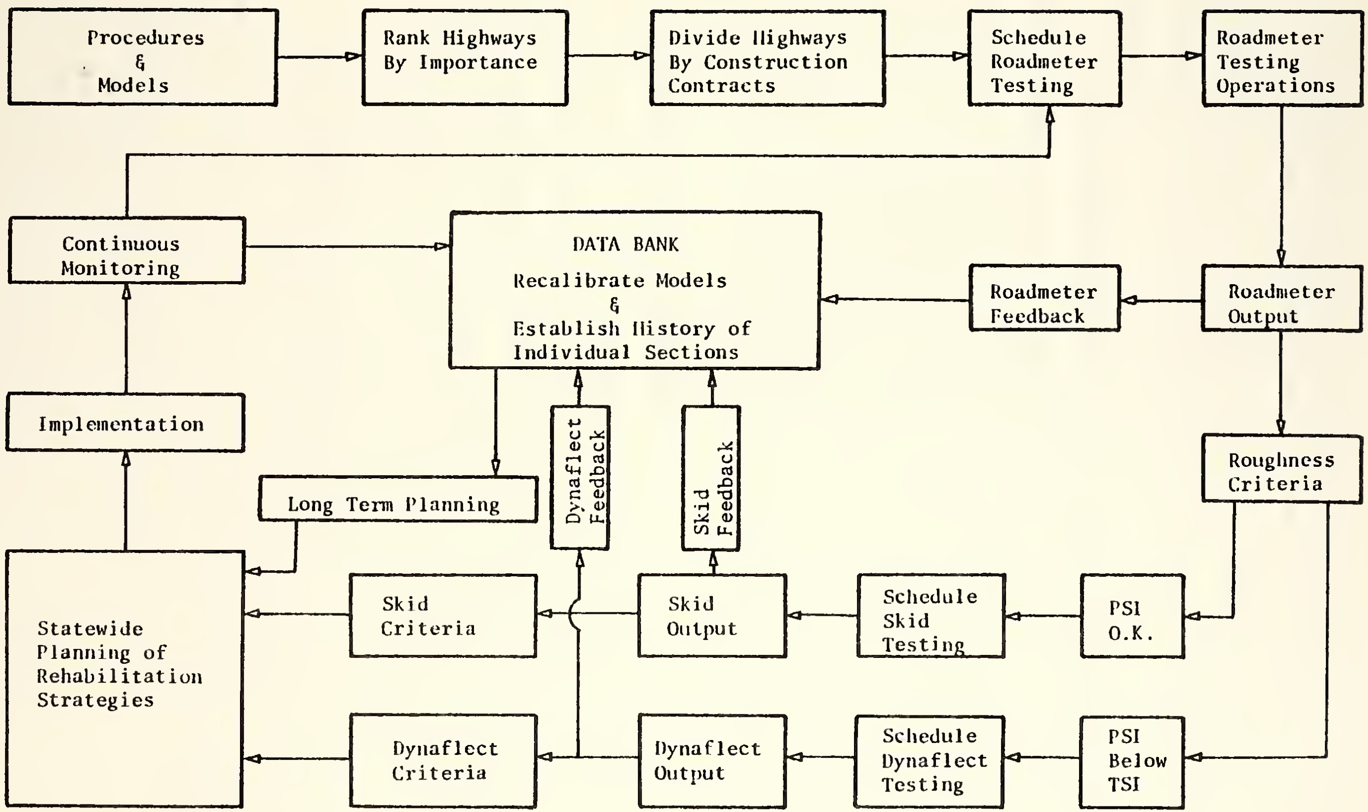


Figure 9.1. A Comprehensive Pavement Evaluation System Utilizing the Roadmeter, the Skid Tester and the Dynaflect

1. Establishing Systematic Testing Procedures and Evaluation Models

It has been established that the three properties used to describe pavement condition and its evaluation are: roughness and skid resistance as a measure of performance and structural evaluation using deflection.

In the preceding chapters of this research, a detailed investigation was made for the variations of pavement properties used for condition evaluation and resulted in the development of optimal testing techniques utilizing the Roadmeter, Dynaflect and the skid tester. In addition, an understanding of the nature of the seasonal variations in pavement properties involved in the evaluation process was developed. This allows making the measurements throughout the testing season and at the same time realizing the seasonal effects on the results.

2. Ranking Highways by Importance

In order to insure efficiency of the field work and facilitate scheduling statewide inventories, all highways within the network need to be ranked depending on their relative importance. One method of ranking would be to use traffic volumes as a criterion. Obviously, interstate highways should be at the top of the list.

3. Divide Highways by Construction Contracts

It has been established that contract sections are well suited to serve as evaluation units since pavement design (type and thickness), materials, construction technique, geometrics and traffic conditions are expected to be uniform on any given contract.

4. Schedule Roadmeter Testing Operations

As previously explained, the Roadmeter is a very efficient piece of equipment that is capable of conducting statewide roughness inventories within a relatively short period of time and at a reasonable cost. From steps 2 and 3 above and after the different highways within the network have been ranked according to their relative importance, the Roadmeter testing operations can be scheduled and its travel routes determined.

5. Roadmeter Testing Operations

On the basis of the investigation conducted in this research, it has been established that roughness variations between the two sides of two-lane highways were found nonsignificant. Therefore, Roadmeter testing on two-lane roads can be made on one side of the road only. However, measurements should be made in the direction carrying the heavier traffic if information is available on traffic directional split or from experience. In industrial areas, testing needs to be performed in the lane carrying the heavier loads. On multi-lane divided highways, testing should be made on both directions of travel since each direction can have its own performance. The testing should be performed on a contract basis. Only one pass of the Roadmeter is needed to provide an accurate measure of the prevailing roughness. The presence of two counting banks in the Roadmeter allows the measurements to be made on consecutive contracts without a need to stop for recording the roughness counts of a previous contract.

The results of the Roadmeter inventory can then be used for providing information relative to the following considerations:

i. The roughness on a specific highway and the roughness of the individual contracts within this highway. This means that the Roadmeter can be used to screen the contracts within a highway and classify them depending on their roughness levels.

ii. The serviceability for the entire network, i.e., the percentage of total mileage for each facility type (interstate, primary, etc.) having a given serviceability level.

iii. Provide a feedback for a data bank. This feedback is very important for the establishment of time performance trends of the individual contracts which allows realistic projections of future serviceability levels at both the project and network levels.

6. Roughness Criteria

It can be seen from Figure 9.1 that the subsequent phases of the evaluation process will branch into two channels depending on the roughness condition of the various highway sections, as follows:

i. The contracts having a serviceability index below a predetermined level of terminal serviceability, TSI. These contracts would be tested for structural adequacy. The Dynaflect would be used to collect the data needed to determine the overlay thickness required for providing a structurally adequate pavement that is capable of carrying the expected traffic loads during its intended service life.

ii. The contracts having serviceability levels above TSI. These contracts would be evaluated for skid resistance.

The premise behind this branching is that since contracts falling below TSI will have to receive some kind of resurface (depending on their structural condition), then it follows that there is not much to be gained from testing them for skid resistance. In addition, making skid measurements on rough pavements would make the measurements rather erratic as well as exposing the equipment to damage.

Therefore, the attention in the skid evaluation phase would have to be focused on those sections having adequate serviceability and are not expected to receive an overlay for several years in order to evaluate their skid resistance and identify skid prone locations.

7. Dynaflect Testing Operations

As discussed earlier, pavements exhibit their highest deflection levels during the spring thaw period. This means that their structural capacities reach minimum levels during this period. Ideally, structural evaluation using deflection measurements should be performed during the spring thaw period in order to achieve a realistic indication of pavement strength. However, the relatively short duration of the spring thaw period does not allow making deflection measurements on a statewide basis. Consequently, it follows that the spring measurements would have to be made on the most important sections candidate for rehabilitation. The remaining sections can be tested throughout the testing season and by applying the appropriate seasonal adjustments spring deflection can be estimated.

The procedure for making deflection measurements using the Dynaflect is described in detail in Chapter 8. The results of the structural adequacy evaluation can then be used for designing overlays.

This phase of the evaluation process would provide a feedback to the data bank as shown in Figure 9.1. The deflection data compiled in the data bank can be used as a valuable source for gaining insight into the performance characteristics of pavement systems of various designs and subjected to a wide variety of traffic conditions.

The roughness evaluation phase identifies those sections in need of rehabilitation. The structural evaluation phase provides guidance for the selection of the type and amount of improvement needed to restore rideability and at the same time provides a pavement structure with adequate strength to withstand traffic loads for several years. The improvement may range from a thin asphalt blanket to an overlay of considerable thickness depending on pavement strength and traffic volumes.

8. Skid Resistance Testing Operations

As mentioned earlier, the emphasis in the skid resistance evaluation phase needs to be focused on those sections having good rideability in order to identify the locations in need of deslicking improvements.

Based on the results of the roughness evaluation phase, the sections that would be evaluated for skid resistance can be listed and scheduled for testing. Detailed discussions on the seasonal changes in skid numbers as well as their variability along contract sections were presented in this report. Consequently, based on the time available for testing and the relative importance of the section under consideration, a suitable number of tests can be performed.

The results of this phase of the evaluation process provide a third feedback to the data bank. The skid data stored in the data bank can be used for establishing decay trends for the skid resistance of highway sections which can be used for assessing future needs.

9. The Data Bank

A data bank is an important feature of a comprehensive and continuous pavement evaluation system. An effective data bank is one that can provide complete and detailed information on the individual highway contracts within a network in a centrally coordinated manner. This information includes:

i. Construction data such as materials used and their properties, pavement design, construction techniques and year opened to traffic. These data are considered essential for the evaluation process and for providing insight into the interaction effects of the various factors affecting pavement performance.

ii. Traffic characteristics such as traffic volumes, directional distribution and percent of trucks in the traffic stream and total equivalent axle loads (EAL).

iii. Geometric features such as number and width of lanes, shoulder type and width, drainage facilities and type of highway (divided or undivided).

iv. Routine maintenance applied to the contract. This should include type of maintenance, materials used and dates.

v. Major maintenance data such as overlay thickness, material type and date opened to traffic.

vi. The results of previous evaluation measurements made on the contract during preceding years and the dates the measurements were made as well as climatic conditions during each year.

The data provided by the data bank can be used to establish time performance trends for highway sections which, in turn, allow projecting their future condition, thereby providing realistic grounds for assessing future rehabilitation needs at both the project and network levels.

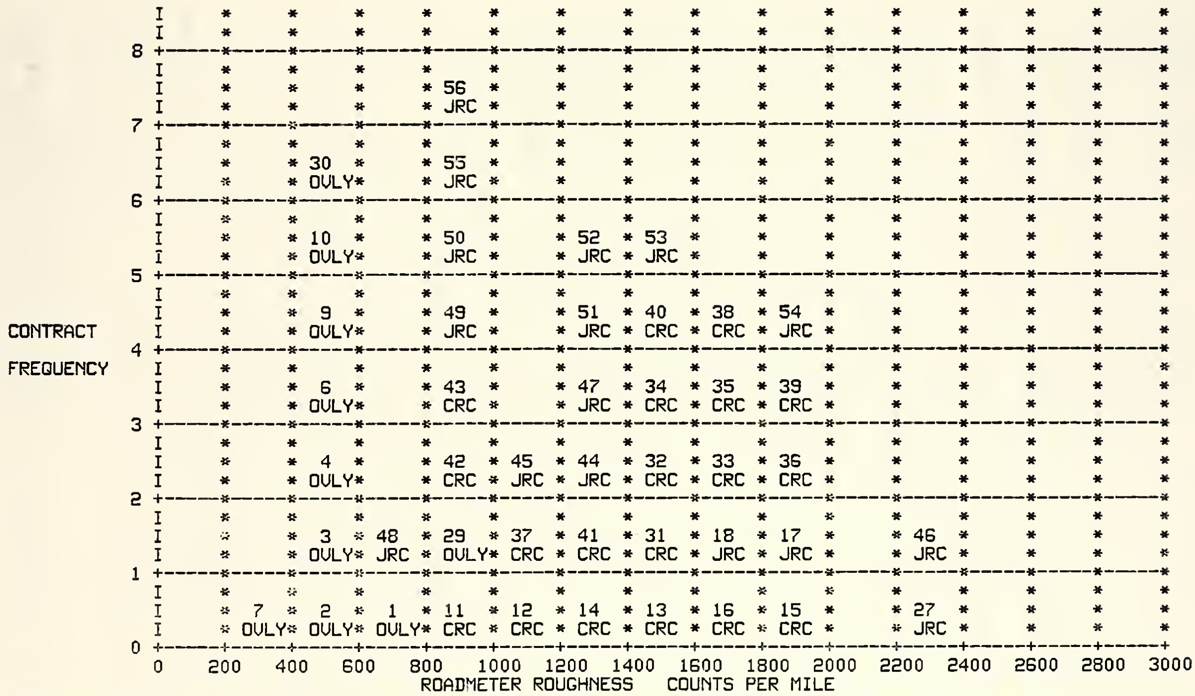
In addition, the data bank would be a source of data for research on the performance characteristics of pavement systems of different designs, constructed with various materials and subjected to a wide range of traffic conditions.

10. Input to the Decision-Making Process

The decision-making process in pavement rehabilitation is complex and is restrained by several factors such as rehabilitation needs, priority programming, political policies and, most of all, limited budgets.

A basic objective of an evaluation system is to provide the management with a clear picture of the entire network as well as specific information relative to the needs of the individual highway segments within the network. Thus, with better and more objective information available on the condition and needs of pavement sections, pavement managers would be able to make rehabilitation decisions on a sound technical basis.

To be of practical use, the information obtained in the evaluation process must be presented to the management in clear and compact forms. As a general example, Figure 9.2 shows a summary of roughness measurements



PSI-CONCRETE	4.44	4.30	4.16	4.02	3.87	3.73	3.59	3.45	3.31	3.17	3.03	2.88	2.74	2.60	2.46
PSI-OVERLAY	4.15	3.94	3.72	3.51	3.29	3.08	2.86	2.64	2.43	2.21					
PSI-ASPHALT	3.85	3.76	3.67	3.58	3.49	3.40	3.32	3.23	3.14	3.05	2.96	2.87	2.78	2.69	2.60

CRC=CONTINUOUSLY REINFORCED CONCRETE PAVEMENT , OVLY=OVERLAY PAVEMENT , JRC=JOINTED REINFORCED CONCRETE PAVEMENT

Figure 9.2. An Example of Using the Roadmeter to Screen Highway Sections Relative to Their Serviceability (NB Travel Lane of I-65)

performed on the northbound travel lane of interstate highway I-65 in Indiana.* The numbers in the cells in Figure 9.2 are the sequence numbers of the contracts as given in Table 9.1 (listed from south to north). It can be readily seen that contracts number 27 and 46 corresponding to contracts R-5856 and R-7275 in Table 9.1, exhibited high roughness levels and, consequently, they deserve an earlier attention. It is pertinent to mention that pavement type is an important factor that must be recognized when determining the serviceability levels of the various contracts. Therefore, the serviceability levels of the different pavements were provided on the horizontal axis of Figure 9.2 (as determined from Table 2.2).

In order to extend the evaluation to the network level, charts similar to the one given in Figure 9.2 can be prepared for all highways in the network. In so doing, it becomes possible to identify the contracts within each highway in need of rehabilitation as indicated by their roughness. A list can then be prepared for candidate contracts. A next stage would be to use the Dynaflect to test these contracts and evaluate the type and amount of improvement required for each contract. Figure 9.2 can also be used to prepare another list for the contracts that would be evaluated for skid resistance and, as explained earlier, these contracts would be the ones above terminal serviceability level.

From the structural and skid resistance evaluation phases, rehabilitation needs can be documented and presented to the management. However, it finally comes down to the top management to balance the

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*The roughness data in this figure were obtained from the road inventory book prepared by R & TC of ISHC.

TABLE 9.1. EXAMPLE OF ROADMETER ROUGHNESS DATA (N.B. TRAVEL LANE OF I-65)

NO	CONTRACT	PAVEMENT *	ROUGHNESS **	AADT
1	R-11237	OVLY	648	17650
2	R-10235	OVLY	550	12440
3	R-11238	OVLY	550	8350
4	R-11239	OVLY	444	8350
5	R-11240	OVLY	---	9187
6	R-10930	OVLY	581	9187
7	R-11255	OVLY	340	8675
8	R-11296	OVLY	---	7412
9	R-10932	OVLY	443	7412
10	R-11297	OVLY	438	10125
11	R-7674	CRC	890	10100
12	R-8159	CRC	1153	10100
13	R-8221	CRC	1485	10150
14	R-7912	CRC	1372	10150
15	R-8001	CRC	1859	11050
16	R-8440	CRC	1633	11725
17	R-5569	JRC	1975	12615
18	R-5876	JRC	1710	13550
19	R-10232	JRC	---	13625
20	R-10347	JRC	---	13625
21	R-10346	JRC	---	13625
22	R-8283	JRC	---	13625
23	R-8255	JRC	---	13625
24	R-7780	JRC	---	13625
25	R-7624	JRC	---	13625
26	R-6333	JRC	---	13625
27	R-5856	JRC	2230	13625
28	R-4710	JRC	---	7375
29	R-10931	OVLY	832	8950
30	R-10209	OVLY	541	10950
31	R-8232	CRC	1585	11400
32	R-8209	CRC	1528	9288
33	R-7935	CRC	1795	5288
34	R-7858	CRC	1428	10450
35	R-7782	CRC	1706	10450
36	R-7715	CRC	1826	10450
37	R-7913	CRC	1149	10375
38	R-7677	CRC	1639	10100
39	R-7633	CRC	1927	8550
40	R-7422	CRC	1560	8550
41	R-7714	CRC	1361	8550
42	R-7676	CRC	916	8550
43	R-7634	CRC	813	8315
44	R-7246	JRC	1312	7875
45	R-7158	JRC	1012	7675
46	R-7275	JRC	2226	7875
47	R-7143	JRC	1202	8400
48	R-7144	JRC	757	8400
49	R-7116	JRC	864	9900
50	R-6600	JRC	814	9900
51	R-6416	JRC	1208	10725
52	R-6538	JRC	1238	10725
53	R-7155	JRC	1398	12625
54	R-6684	JRC	1805	25250
55	R-6908	JRC	997	29025
56	R-6929	JRC	812	29025

* OVLY=OVERLAY , CRC=CONTINUOUSLY REINFORCED , JRC=JOINTED REINFORCED CONCRETE

** ROADMETER COUNTS PER MILE.

--- DATA NOT AVAILABLE.

needs to the available resources, set the priorities and trigger the improvements.

As can be seen from Figure 9.1, another input to the decision makers relative to future rehabilitation needs comes from the integration of the projected condition of highway sections from their time performance trends as established in the data bank within the framework of the feedback system. This projection of future needs can be very useful when future fiscal needs are documented to the taxpayers and legislators.

11. Continuous Monitoring

Due to the fact that highway pavements deteriorate with time, highway programs must consider continuous rehabilitation operations to maintain highways in a useable and safe condition. Therefore, pavement evaluation has to be a dynamic process in order to provide updated information on the present status and the performance characteristics of pavement sections as well as their present and future rehabilitation needs. The continuous monitoring process will assure an automatic and continuous feedback into the memory of the evaluation system -- the data bank.

CHAPTER 10

SUMMARY

One of the key components of a pavement management system is condition evaluation. This process is vital for providing the decision makers with objective and updated information on the status and rehabilitation needs of the pavement sections within the highway network.

It has been established that for nondestructive pavement condition evaluation purposes, three pavement properties need to be tested: roughness, structural adequacy and skid resistance.

It has been realized that for a comprehensive evaluation system highway contract sections should be used as evaluation units. Therefore, specific procedures were needed relative to techniques for measuring pavement properties on the evaluation units (i.e., the contract sections). In addition, there was a need to examine the seasonal changes in the measured properties so that they can be accounted for in the evaluation process.

To achieve the objectives of the investigation, two main experiments were designed to collect and analyze data from in-service test sections in Indiana. Each of the two experiments included the four primary pavement types -- asphalt, overlay, JRC and CRC pavements. Both experiments were concerned with examining the three pavement properties previously mentioned (roughness, structural adequacy and skid resistance) as measured by the Roadmeter, Dynaflect and skid tester, respectively.

The first experiment aimed at examining the seasonal changes in pavement properties. Deflection data collected on a seasonal basis showed that seasonal changes have significant effects on the deflections of asphalt, overlay and JRC pavements. Analysis was made on data available from the literature and resulted in the development of correlations that can be used for estimating the maximum spring deflection of flexible pavements from measurements made during the summer and fall months.

The analysis of the roughness data indicated that the seasonal effects on the measured roughness were nonsignificant for all pavement types included in the investigation. This means that Roadmeter roughness measurements can be conducted throughout the testing season and yet provide representative and comparable values of the actual condition of the pavements evaluated. The analysis also showed that the yearly rate of change in pavement roughness varied from year to year and from section to section reflecting the inherent performance characteristics of different highway sections having different pavement designs, material properties, construction techniques and traffic conditions. This indicates the need for continuous monitoring of pavement sections in order to establish their characteristic performance trends so that a realistic projection of their expected condition can be made.

Regression models were developed for each of the four pavement types considered in the research to predict the present serviceability index, PSI, from Roadmeter measurements. These models are simple and suitable for practical applications.

The seasonal changes in pavement skid resistance were investigated for both asphalt and concrete surfaces. Significant differences were found between the spring and fall skid numbers with the spring values being higher by about 5-10 SN for asphalt surfaces and by about 5 SN for concrete surfaces.

An investigation was made to examine the effect of the error in estimating the representative deflection on the expected service life of the designed asphalt overlay at different levels of traffic volumes for flexible pavements. This analysis provides useful input to the selection of an optimal Dynaflect testing intensity.

The second experiment was concerned with examining the variability of pavement properties along contract sections. An understanding was developed relative to the factors involved in making evaluation measurements on contract sections as follows:

Deflection variability studies indicated that pavement deflections vary significantly from location to location within a given contract. Therefore, it is recommended to distribute the deflection measurements on the entire length of the contract and at the same time making enough tests in order to estimate the representative deflection with a reasonable accuracy. For flexible pavements a Dynaflect testing intensity of five tests per mile for low-volume roads and 10 tests per mile for high-volume roads seems to be adequate for both practical and accuracy considerations. A testing intensity of 10 test stations per mile seemed adequate for overlay and jointed concrete pavements. At each test station overlay pavements need to be tested at the reflection crack and at the mid-span positions. Jointed concrete pavement should be tested at the joint and at the mid-span positions. For continuously reinforced concrete pavements a testing intensity of 10 tests per mile is expected to provide good results.

Roughness variability studies showed that significant variations existed among the different locations within the same contract thereby requiring the roughness measurements to cover all the contract being evaluated so that a realistic indication of the prevailing roughness can be obtained. The analysis also showed that one pass of the Road-meter on the contract under evaluation is sufficient for providing accurate results. Measurements on two-lane highways showed nonsignificant differences between the two sides of the two-lane highway. Thus, roughness can be estimated with reasonable accuracy from measurements made on one direction of travel. However, good judgment and experience should be used when selecting the direction to be tested.

Skid resistance variability studies showed that for the four pavement types considered in the research, skid numbers measured on different locations in the same contract can have high variability. The difference in skid numbers between the two lanes of two-lane highways was found to be generally nonsignificant. The skid variability studies resulted in the development of correlations that can be used for selecting the number of required skid tests per mile depending on the desired accuracy. Based on the results obtained from the skid variability studies, it would be necessary to spread the skid measurements on the contract being tested at a reasonable intensity in order to effectively assess the skid resistance of the section being evaluated.

In order to put the entire evaluation process in perspective, a framework for a comprehensive evaluation system was presented. The various phases of the evaluation process were discussed. The Roadmeter due to its speed and ease of operation would be used to screen the many contracts in the network and identify the ones in need of rehabilitation to be further tested by the Dynaflect for structural adequacy. The skid tester would be used to evaluate the skid resistance of the sections with good rideability as also identified in the roughness evaluation phase. A data bank is considered to be an essential component of a continuous and comprehensive evaluation system. The continuous monitoring of the network would provide a constant feedback into the data bank which, in turn, would keep the management up-to-date with the present and future status and rehabilitation needs at both the project as well as the network levels.

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APPENDICES

APPENDIX A

GEOGRAPHIC LOCATIONS OF TEST SECTIONS (SEASONAL TESTING PROGRAM)

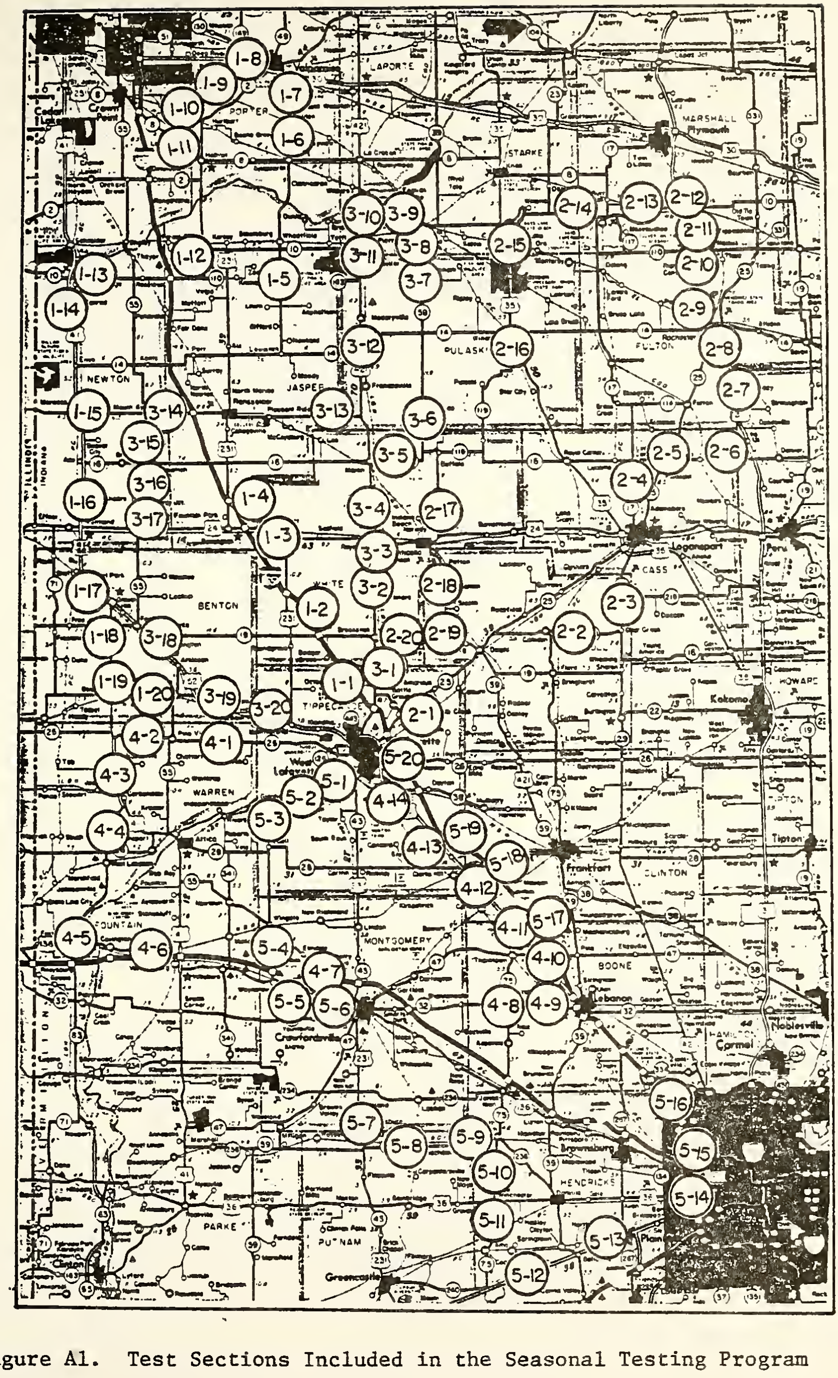

Figure A1. Test Sections Included in the Seasonal Testing Program

TABLE A1. GEOGRAPHIC LOCATIONS OF TEST SECTIONS (SEASONAL TESTING)

LOOP & SECTION	PAVEMENT	HIWY-DIRCTN		COUNTY	LOCATION
1-1	CRCP	I-65	NBL	TPCN	4.0 FROM JCT. I-65/SR-43 AT MILE MARKER 182.
1-2	CRCP	I-65	NBL	WHIT	0.5 FROM MILE M ARKER 188 AT I-65 SIGN.
1-3	CRCP	I-65	NBL	WHIT	0.9 FROM MILE MARKER 197 0.4 FROM CO. ROAD 1100 W.
1-4	CRCP	I-65	NBL	JSPR	AT MILE MARKER 200.
1-5	ASPH	SR-49	NBL	JSPR	8.5 FROM JCT. SR-49/SR-14 3.5 MILES FROM SR-10.
1-6	JRCP	SR-49	NBL	PRTR	0.8 FROM JCT. SR-49/SR-8.
1-7	JRCP	SR-49	NBL	PRTR	5.5 FROM JCT. SR-49/SR-8 4.1 FROM END OF SEC. 1-6
1-8	OVLY	US-30	WBL	PRTR	1.0 FROM JCT. US-30/SR-49 NATIONAL GUARD ARMORY SIGN.
1-9	OVLY	SR-2	WBL	PRTR	1.5 FROM JCT. SR-2/US-30 AT 55 MPH SPEED SIGN.
1-10	OVLY	SR-2	WBL	PRTR	4.0 FROM JCT. SR-2/US-30 DOWNHILL SOUTH CO.ROAD 275W.
1-11	OVLY	SR-2	WBL	PRTR	10.0 FROM JCT. SR-2/US-30 5.4 FROM END OF SEC. 1-10
1-12	ASPH	SR-10	WBL	JSPR	8.0 FROM JCT. SR-2/US-231 1.0 FROM JCT. SR-10/18TH ST. DEMOTTE
1-13	ASPH	SR-10	WBL	NWTN	2.7 FROM JCT. SR-10/SR-55
1-14	JRCP	US-41	SBL	NWTN	0.9 FROM JCT. US-41/SR-10
1-15 *	JRCP	US-41	SBL	NWTN	3.5 FROM JCT. US-41/SR-14
1-16	JRCP	US-41	SBL	NWTN	3.0 FROM JCT. US-41/SR-16
1-17	JRCP	US-41	SBL	BNTN	5.4 FROM JCT.US-41/US-24
1-18	JRCP	US-41	SBL	BNTN	0.3 FROM JCT. US-41/SR-18
1-19	JRCP	US-41	SBL	BNTN	4.2 FROM JCT. US-41/SR-18 3.3 FROM END OF SEC. 1-18
1-20	ASPH	SR-352	EBL	BNTN	2.7 FROM JCT. US-41/SR-352
2-1	OVLY	SR-25	NBL	TPCN	4.1 FROM JCT.I-65/SR-25 1.1 FROM JCT. SR-225/SR-25
2-2	ASPH	SR-218	EBL	CARO	1.2 FROM JCT. SR-75/SR-218
2-3	ASPH	SR-29	NBL	CARO	1.3 FROM JCT. SR-29/SR-218
2-4	OVLY	SR-17	NBL	CASS	5.0 FROM LOGANSPORT NORTH CITY LIMIT SIGN
2-5	ASPH	SR-16	EBL	CASS	1.2 FROM JCT. SR-16/SR-17
2-6	ASPH	SR-16	EBL	CASS	6.1 FROM JCT. SR-16/SR-25
2-7 *	OVLY	US-31	NBL	MAMI	5.8 FROM JCT. US-31/SR-16
2-8	CRCP	US-31	NBL	FLTN	13.1 FROM JCT. US-31/SR-16 1.0 FROM WABASH ROAD NORTH
2-9	CRCP	US-31	NBL	FLTN	1.8 FROM JCT. US-31/SR-14
2-10 *	CRCP	US-31	NBL	FLTN	3.8 FROM JCT. US-31/SR-14

* WERE NOT INCLUDED IN 1979-1980 TESTING.

TABLE A1 (CONTINUED) .

LOOP & SECTION	PAVEMENT	HIWY-DIRCTN	COUNTY	LOCATION
2-11 *	CRCP	US-31 NBL	FLTN	6.0 FROM JCT. US-31/SR-14
2-12	JRCP	US-31 NBL	MARL	1.3 FROM JCT. US-31/SR-110
2-13	ASPH	SR-10 WBL	MARL	1.3 FROM JCT. US-31/SR-10
2-14	ASPH	SR-10 WBL	MARL	1.9 FROM JCT. SR-10/SR-17 S
				(SECOND JCT.)
2-15	ASPH	US-35 SBL	PULK	2.3 FROM JCT. US-35/SR-10
2-16	ASPH	SR-119 SBL	PULK	1.7 FROM JCT.US-35/SR-119
2-17	ASPH	SR-39 SBL	WHIT	4.9 FROM JCT. SR-39/SR-119
2-18	ASPH	US-421 SBL	CARO	5.0 FROM JCT. US-421/US-24
2-19	ASPH	US-421 SBL	CARO	8.5 FROM JCT. US-421/US-24
2-20	OVLY	SR-18 WBL	WHIT	3.4 FROM JCT. SR-18/US-421
3-1 *	OVLY	SR-25 SBL	TPCN	0.8 FROM JCT. SR-225/SR-43
3-2 *	OVLY	SR-25 SBL	TPCN	4.5 FROM JCT. SR-25/SR-43
3-3	OVLY	SR-25 SBL	TPCN	9.6 FROM JCT. SR-25/SR-43
3-4	ASPH	SR-25 SBL	MONT	10.5 FROM JCT. SR-25/SR-28 W
3-5	OVLY	US-136 EBL	MONT	1.6 FROM JCT. US-136/SR-25
3-6	OVLY	US-136 EBL	MONT	6.0 FROM JCT. US-136/SR-25
				0.2 FROM RR CROSSING
3-7	OVLY	US-231 EBL	MONT	1.0 FROM JCT. US-231/SR-234
3-8	ASPH	SR-236 EBL	PTAM	2.0 FROM JCT. SR-236/US-231
3-9	ASPH	SR-236 EBL	PTAM	9.8 FROM JCT. SR-236/US-231
				7.2 FROM END OF SEC. 3-8
3-10 *	ASPH	SR-75 EBL	HERK	4.5 FROM JCT. SR-75/SR-236
3-11	ASPH	SR-75 SBL	HERK	1.0 FROM JCT. SR-75/US-36
3-12 *	OVLY	US-40 EBL	HERK	4.3 FROM JCT. US-40/SR-75
3-13 *	OVLY	US-40 EBL	HERK	12.5 FROM JCT. US-40/SR-75
				AT MAIL BOX
3-14	JRCP	I-465 NBL	MARN	1.7 FROM EXIT 13 B
				0.75 FROM MILE MARKER 14
3-15	JRCP	I-465 NBL	MARN	AT MILE MARKER 18
3-16	OVLY	I-65 NBL	HERK	33.5 FROM JCT. I-65/I-465
				AT MILE MARKER 127
3-17	CRCP	I-65 NBL	CLTN	2.0 FROM CLINTON CO. LINE
				AT MILE MARKER 152
3-18	CRCP	I-65 NBL	CLTN	5.0 FROM TIPPECANOE CO. LINE
				AT MILE MARKER 155
3-19	CRCP	I-65 NBL	TPCN	1.5 FROM TIPPECANOE CO. LINE
				AT MILE MARKER 162
3-20	CRCP	I-65 NBL	TPCN	12.5 FROM TIPPECANOE CO. LIN
				AT MILE MARKER 173
4-1	ASPH	SR-26 WBL	WARN	0.4 FROM WARREN CO. LINE
4-2	ASPH	SR-26 WBL	WARN	9.7 FROM WARREN CO. LINE
				2.2 FROM JCT. SR-26W/SR-55
4-3	JRCP	US-41 SBL	WARN	3.1 FROM JCT. US-41/SR-26
4-4 *	JRCP	SR-63 SBL	WARN	0.1 FROM JCT. US-41/SR-63
4-5 *	JRCP	SR-63 SBL	WARN	0.3 FROM JCT. SR-63/US-136

* WERE NOT INCLUDED IN 1979-1980 TESTING.

TABLE A1 (CONTINUED) .

LOOP & SECTION	PAVEMENT	HIWY-DIRCTN		COUNTY	LOCATION
4-6	JRCP	I-74	EBL	FNTN	AT MILE MARKER 10
4-7	JRCP	I-74	EBL	MONT	AT MILE MARKER 27
4-8	ASPH	SR-32	EBL	BOON	0.8 FROM JCT. SR-32/SR-75
4-9	ASPH	SR-32	EBL	BOON	3.9 FROM JCT. SR-32/SR-75
					2.5 FROM END OF SEC. 1-8
4-10	OVLY	US-52	WBL	BOON	0.3 FROM JCT. US-52/I-65
					JUST BEFORE STATE GARAGE
4-11 *	JRCP	US-52	WBL	BOON	1.9 FROM JCT. US-52/SR-47
4-12 *	OVLY	US-52	WBL	CLTN	3.1 FROM CLINTON CO. LINE
4-13	OVLY	US-52	WBL	TPCN	2.0 FROM TIPPECANOE CO. LINE
					1.7 FROM JCT. US-52/SR-28
4-14	OVLY	US-52	WBL	TPCN	9.4 FROM TIPPECANOE CO. LINE
5-1	OVLY	SR-43	NBL	TPCN	1.6 FROM JCT. I-65/SR-43
5-2	OVLY	SR-43	NBL	WHIT	4.5 FROM JCT. SR-43/SR-18W
					(SECOND JCT.)
5-3	OVLY	SR-43	NBL	WHIT	8.3 FROM JCT. SR-43/SR18W
					3.1 FROM END OF SEC. 5-2
5-4 *	OVLY	US-421	NBL	WHIT	1.0 FROM JCT. US-24/US-421
					0.5 FROM RR CROSSING
5-5	ASPH	SR-16	EBL	WHIT	1.1 FROM JCT. SR-16/US-421
					ACROSS FROM LARGE TREE
5-6	ASPH	SR-39	NBL	WHIT	1.4 FROM JCT.SR-39/SR-16
5-7	ASPH	SR-39	NBL	PULK	4.5 FROM JCT. SR-39/SR-14
					AT NATURAL GAS PIPE MARKER 6
5-8	ASPH	SR-39	NBL	STRK	1.0 FROM STARKE CO. LINE
5-9	ASPH	SR-10	WBL	STRK	1.5 FROM JCT. SR-39/SR-10
					0.1 AFTER RR TRACKS
5-10	ASPH	SR-10	WBL	STRK	3.6 FROM JCT. SR-39/SR-10
					ACROSS FROM PUMP STATION
5-11	ASPH	US-421	SBL	STRK	0.2 FROM JCT. US-421/SR-10
5-12	ASPH	US-421	SBL	PULK	0.6 FROM JCT. US-421/SR-14
5-13	ASPH	SR-114	WBL	PULK	1.7 FROM JCT.SR-114/US-421
5-14	ASPH	SR-114	WBL	JSPR	0.6 FROM JCT. I-65/SR-114
5-15	ASPH	SR-55	SBL	NWTN	0.6 FROM JCT. SR-55/SR-114
5-16 *	ASPH	SR-55	SBL	NWTN	4.5 FROM JCT. SR-55/SR-114
5-17	ASPH	SR-55	SBL	NWTN	6.5 FROM JCT. SR-55/SR-114
5-18	OVLY	US-52	EBL	BNTN	0.3 FROM JCT. US-52/SR-18E
5-19 *	JRCP	US-52	EBL	BNTN	5.4 FROM JCT. US-52/SR-352
5-20	JRCP	US-52	EBL	TPCN	0.5 FROM TIPPECANOE CO. LINE

* WERE NOT INCLUDED IN 1979-1980 TESTING.

APPENDIX B

PERFORMANCE STUDIES OF PAVEMENT SERVICEABILITY

TABLE B1. ROADMETER ROUGHNESS DATA (SEASONAL TESTING)

LOOP& SECTN	PAVMT TYPE	F-77	F-78	SEASON-YEAR S-79	F-79	S-80
1-5	ASPH	2051	2380	2270	2006	1692
1-12	ASPH	957	1196	1138	1016	1254
1-13*	ASPH	3135	3439	3333	1444	1333
1-20	ASPH	720	---	1302	1151	1413
2-2 *	ASPH	800	---	---	391	366
2-3	ASPH	267	263	457	279	316
2-5	ASPH	2091	---	---	1934	2106
2-6 *	ASPH	3453	---	---	1118	1237
2-13*	ASPH	2096	---	---	956	1026
2-14*	ASPH	1943	---	---	847	1035
2-15	ASPH	901	---	730	---	854
2-16	ASPH	2075	---	2064	1703	1607
2-17	ASPH	1237	---	1505	1421	1372
2-18	ASPH	702	---	711	821	639
2-19	ASPH	574	---	---	655	768
3-4	ASPH	1211	---	1323	1234	1392
3-8	ASPH	857	---	900	964	879
3-9	ASPH	906	---	979	1027	965
3-11	ASPH	1023	---	---	1170	1429
4-1	ASPH	1294	---	---	1484	1541
4-2	ASPH	1585	---	---	1147	1366
4-8 *	ASPH	678	---	---	247	270
4-9 *	ASPH	934	---	---	304	363
5-5 *	ASPH	3308	---	---	921	880
5-6	ASPH	1517	---	1523	1212	1564
5-7	ASPH	2570	---	---	2080	2133
5-8	ASPH	1110	633	724	1040	659
5-9	ASPH	563	---	501	588	537
5-10	ASPH	649	940	933	970	1000
5-11	ASPH	613	773	656	922	920
5-12	ASPH	250	---	307	312	375
5-13	ASPH	2089	---	1925	2150	2224
5-14	ASPH	954	962	847	1110	1123
5-15*	ASPH	3791	---	---	1617	1616
5-17*	ASPH	2800	---	---	1007	987

* RECEIVED ASPHALT OVERLAYS

TABLE B1 (CONTINUED)

LOOP& SECTN	PAVMT TYPE	F-77	F-78	SEASON-YEAR S-79	F-79	S-80
1-8	OVLY	944	---	1308	1195	1237
1-9	OVLY	258	322	378	312	366
1-10	OVLY	220	316	355	290	294
1-11	OVLY	---	---	302	271	330
2-1	OVLY	284	---	618	309	325
2-4 *	OVLY	1100	---	---	211	246
2-20	OVLY	1428	1349	1280	1262	1363
3-3 *	OVLY	989	---	---	382	302
3-5 *	OVLY	889	---	---	278	347
3-6 *	OVLY	1336	---	---	263	310
3-7	OVLY	240	---	337	412	327
3-16	OVLY	312	---	436	465	558
4-10	OVLY	551	680	671	653	588
4-13	OVLY	467	539	664	566	732
4-14	OVLY	615	376	---	313	349
5-1	OVLY	154	---	208	196	240
5-2	OVLY	403	---	583	525	609
5-3	OVLY	2575	742	792	860	962
5-18	OVLY	333	358	359	385	525
1-6	JRC	883	1142	883	1115	765
1-7	JRC	610	---	632	739	567
1-14	JRC	397	501	436	492	456
1-16	JRC	1065	1350	1255	1459	1352
1-17	JRC	620	853	846	933	774
1-18	JRC	493	---	733	688	680
1-19	JRC	366	---	572	540	625
2-12	JRC	399	---	430	478	461
3-14	JRC	1253	---	1600	1430	1639
3-15	JRC	637	---	707	753	757
4-3	JRC	529	721	670	704	662
4-7	JRC	781	---	1069	1135	966
5-20	JRC	973	1203	1063	1196	1054
1-1	CRC	834	1073	1335	1146	949
1-2	CRC	962	1207	1216	1297	1041
1-3	CRC	357	467	475	529	328
1-4	CRC	255	498	443	569	377
2-8	CRC	413	442	563	415	425
2-9	CRC	319	---	323	313	325
3-17	CRC	916	---	1223	1241	1160
3-18	CRC	727	---	878	840	925
3-19	CRC	398	---	515	501	522
3-20	CRC	760	---	784	922	955

* RECEIVED ASPHALT OVERLAYS.

APPENDIX C

VARIABILITY OF PAVEMENT ROUGHNESS OVER CONTRACT SECTIONS

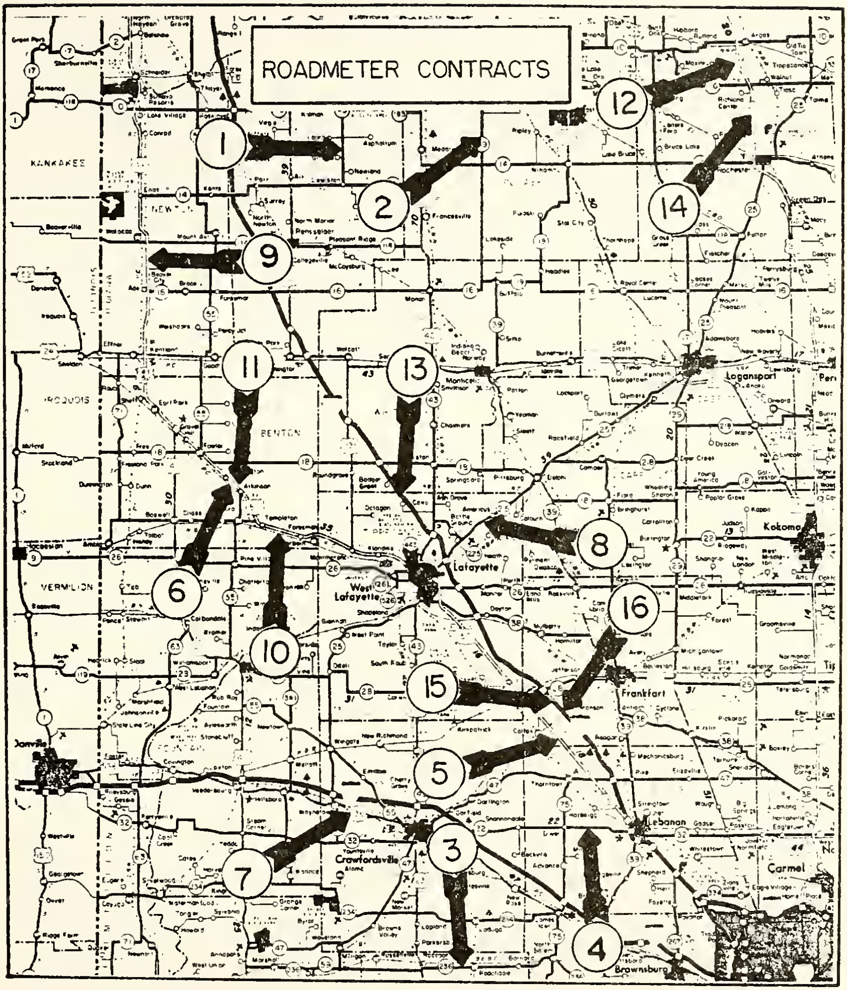

Figure C1. Test Contracts for Roughness Variability Study

TABLE C1. GEOGRAPHIC LOCATIONS OF ROUGHNESS VARIABILITY STUDY CONTRACTS.

CONTRACT	PVMT	HIGHWAY	DRCTN	GEOGRAPHIC LOCATION
1	ASPH	SR-49	NBL	0.5 FROM JCT.SR-14/SR-49
2	ASPH	SR-39	NBL	0.7 FROM JCT. SR-14E/SR-39
3	ASPH	SR-236	EBL	1.5 FROM JCT. SR-236/US-231N
4	ASPH	SR-32	EBL	1.0 FROM JCT. SR-75/SR-32
5	OVLY	US-52	WBL	1.0 FROM BOONE-CLNTN CO.LINE
6	OVLY	US-52	EBL	0.3 FROM JCT.SR-18E/US-52
7	OVLY	US-136	EBL	1.5 FROM JCT.SR-25N/US-136
8	OVLY	SR-25	NBL	0.8 FROM JCT.SR-25/SR-225
9	JRCP	US-41	SBL	0.1 FROM JCT.SR-114/US-41
10	JRCP	US-52	WBL	1.4 FROM BENTN-TPCNOE CO.LINE
11	JRCP	US-52	WBL	0.4 FROM JCT. US-52/SR-55S
12	JRCP	US-31	NBL	0.4 FROM JCT. US-31/SR-110
13	CRCP	I-65	NBL	3.3 FROM JCT. I-65/SR-43
14	CRCP	US-31	NBL	0.6 FROM TPCNOE RIVER
15	CRCP	I-65	SBL	0.7 FROM JCT. I-65/SR-28
16	CRCP	I-65	NBL	2.1 FROM BOONE-CLNTN CO.LINE

TABLE C2. ROUGHNESS DATA FOR VARIABILITY STUDIES.

CONTRACT NO.	PAVMT TYPE	DIRCTN NO.	PASS NO.	TEST LOCATION 1	2	3
1	ASPH	1	1	3898	2824	4195
			2	3370	2765	4342
			3	3352	2943	4265
		2	1	3880	2316	3566
			2	3814	2374	3481
			3	3324	2355	3451
2	ASPH	1	1	2791	2914	4258
			2	3057	2842	4180
			3	2966	2951	4077
		2	1	2785	3244	3559
			2	2938	3365	3799
			3	2780	2998	3737
3	ASPH	1	1	2068	1623	1813
			2	1894	1712	1669
			3	2079	1871	1826
		2	1	2333	2118	2338
			2	2288	2100	2402
			3	2121	2209	2314
4	ASPH	1	1	639	378	510
			2	584	537	603
			3	600	579	662
		2	1	881	596	1015
			2	931	570	834
			3	893	542	860
5	OVLY	1	1	1646	1502	1525
			2	1673	1599	1530
			3	1466	1630	1580
6	OVLY	1	1	755	1351	1145
			2	778	1528	1223
			3	803	1470	1176
7	OVLY	1	1	727	806	628
			2	677	879	637
			3	716	952	674
		2	1	638	684	706
			2	612	672	694
			3	667	650	713
8	OVLY	1	1	923	1223	1260
			2	854	1265	1426
			3	1007	1148	1217
		2	1	1516	1313	1455
			2	1430	1375	1636
			3	1390	1445	1752
9	JRCP		1	2053	2393	2255
			2	1802	2415	2248
			3	2098	2330	2202
10	JRCP		1	1865	1569	1466
			2	1944	1646	1484
			3	1912	1728	1522
11	JRCP		1	1397	1474	2936
			2	1415	1537	2840
			3	1350	1526	2950
12	JRCP		1	845	520	1325
			2	901	921	1430
			3	818	826	1150
13	CRCP		1	2235	1672	2775
			2	2277	1707	2708
			3	2458	1655	2631
14	CRCP		1	760	1137	1303
			2	734	1201	1266
			3	708	1261	1344
15	CRCP		1	1805	2501	3032
			2	1747	2475	2565
			3	1643	2464	2668
16	CRCP		1	2177	2048	1386
			2	2287	2061	1468
			3	2175	2037	1416

APPENDIX D

SEASONAL CHANGES IN PAVEMENT SKID RESISTANCE

TABLE D1. SKID RESISTANCE DATA (SEASONAL TESTING)

LOOP & SECTN	SUR-FACE TYPE	SEASON-YEAR F-77 AVG	SD	S-78 AVG	SD	F-79 AVG	SD	S-80 AVG	SD
1-9	ASPH	51.1	2.2	54.7	2.3	53.2	2.1	60.9	3.1
1-12	ASPH	43.3	4.1	42.7	4.6	35.2	2.8	50.6	5.4
2-3	ASPH	46.2	2.5	51.7	1.6	45.1	1.4	58.8	1.5
2-20	ASPH	52.8	2.4	49.3	1.8	42.5	2.1	54.8	1.9
4-10	ASPH	48.3	3.9	36.7	3.2	34.2	1.6	44.5	2.4
4-13	ASPH	46.3	1.9	55.2	1.8	50.5	3.4	62.8	2.5
5-3	ASPH	46.0	3.5	43.6	1.8	42.6	2.0	37.7	4.9
5-7	ASPH	52.8	2.3	48.0	7.1	51.9	3.0	59.0	12.1
5-8	ASPH	55.1	1.6	57.2	5.9	56.6	4.0	62.8	4.5
5-10	ASPH	29.8	3.6	39.3	1.1	31.4	6.2	48.9	6.0
5-11	ASPH	38.4	2.2	43.1	0.4	41.2	1.4	44.2	3.2
5-14	ASPH	45.6	1.9	45.8	4.5	45.7	1.4	54.6	2.2
5-18	ASPH	42.9	4.5	47.5	3.8	37.7	4.9	47.6	4.4
1-1	CONC	37.7	2.4	38.3	0.9	32.1	2.5	38.0	3.2
1-2	CONC	40.1	3.0	38.4	3.0	31.9	2.9	38.7	2.9
1-6	CONC	42.4	1.8	39.7	2.2	36.2	1.5	35.2	3.1
1-14	CONC	38.3	2.2	42.7	1.9	35.6	2.7	44.4	2.6
1-16	CONC	43.9	6.2	32.4	18.2	35.8	4.0	47.2	2.8
1-17	CONC	42.7	0.6	42.2	3.0	33.2	1.6	45.6	1.6
2-8	CONC	40.4	2.0	41.7	2.4	36.7	4.7	40.6	3.5
4-3	CONC	54.0	1.1	58.0	2.0	52.2	1.5	64.4	2.5
5-20	CONC	37.0	1.9	37.6	3.4	33.5	2.5	39.6	2.0

APPENDIX E

VARIABILITY OF PAVEMENT SKID RESISTANCE OVER CONTRACT SECTIONS

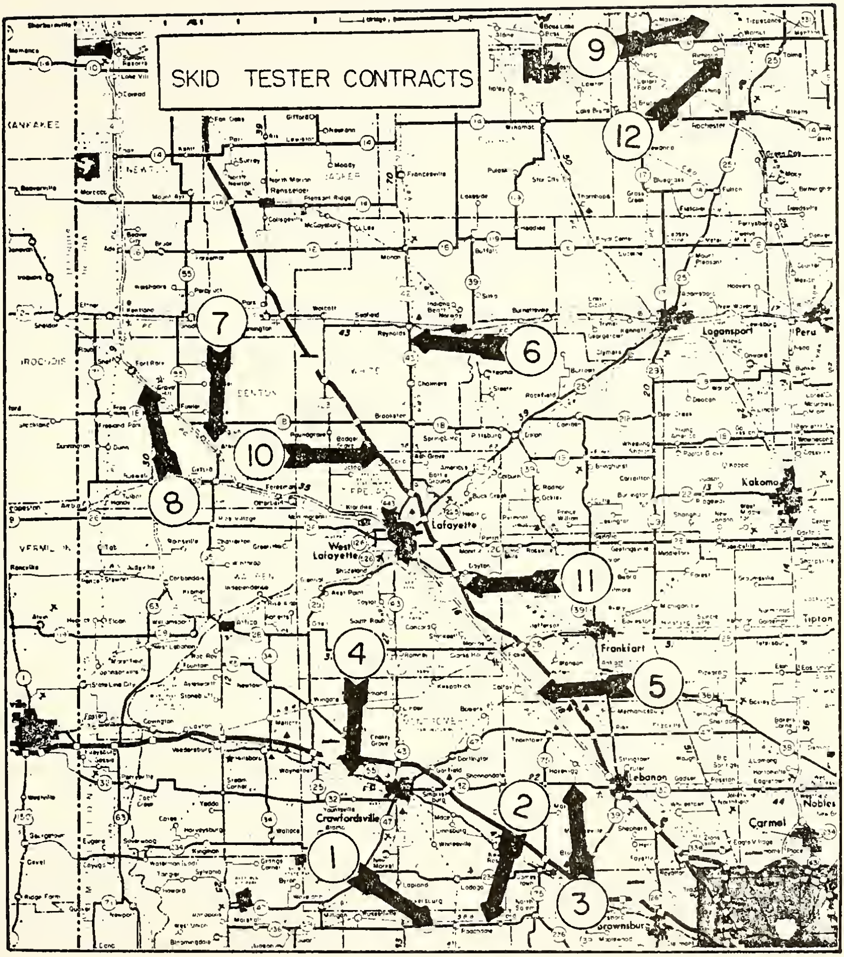

Figure E1. Test Contracts for Skid Resistance Variability Study

TABLE E1. GEOGRAPHIC LOCATIONS OF SKID VARIABILITY STUDY CONTRACTS.

CONTRACT	PVMT	HIGHWAY	DRCTN	GEOGRAPHIC LOCATION
1	ASPH	SR-236	EBL	1.5 FROM U.S-231 NORTH
2	ASPH	SR-236	EBL	1.45 FROM ROACHDALE
3	ASPH	SR-32	EBL	STARTS AT SR-75
4	OVLY	US-136	EBL	STARTS AT SR-25 SOUTH
5	OVLY	SR-52	WBL	0.2 FROM BOONE-CLNTN CO. LINE
6	OVLY	SR-43	NBL	NORTH OF CHALMERS
7	JRCP	US-52	WBL	STARTS AT SR-55 SOUTH
8	JRCP	US-41	SBL	1.1 FROM NEWTON-BENTON CO.LINE
9	JRCP	US-31	NBL	STARTS AT SR-110
10	CRCP	I-65	NBL	2.8 FROM SR-43
11	CRCP	I-65	NBL	4.2 FROM CLNT-TIPCNOE CO.LINE
12	CRCP	US-31	NBL	STARTS AT TIPPECANOE RIVER

TABLE E2. SKID RESISTANCE VARIABILITY STUDY DATA

CONTRACT & LOCATION	PAVE-MENT TYPE	TESTING DIREC-TION	SKID NUMBER (SN) AVG	SD
1-1	ASPH	1	53.4	6.0
		2	54.7	3.7
1-2		1	57.6	6.5
		2	56.1	4.0
1-3		1	58.8	4.4
		2	49.0	8.4
2-1	ASPH	1	54.2	2.6
		2	46.2	9.1
2-2		1	54.6	8.0
		2	48.6	6.9
2-3		1	45.4	9.8
		2	39.2	10.7
3-1	ASPH	1	53.1	2.9
		2	55.2	3.3
3-2		1	51.4	2.7
		2	54.7	2.9
3-3		1	54.1	2.7
		2	54.3	2.3
4-1	OVLY	1	56.1	2.0
		2	57.7	2.4
4-2		1	59.5	1.1
		2	57.9	1.7
4-3		1	58.2	2.1
		2	57.6	3.2
5-1	OVLY		58.4	1.9
5-2			58.7	3.1
5-3			53.9	2.6
6-1	OVLY	1	39.8	4.6
		2	40.1	4.1
6-2		1	42.4	3.1
		2	36.7	4.1
6-3		1	39.9	4.3
		2	27.6	5.5
7-1	JRC		50.6	2.3
7-2			47.5	5.0
7-3			47.6	3.4
8-1	JRC		44.7	4.0
8-2			43.5	2.5
8-3			46.5	1.5
9-1	JRC		33.2	5.6
9-2			35.5	5.2
9-3			30.7	6.6
10-1	CRC		25.3	7.2
10-2			40.5	1.9
10-3			40.4	4.4
11-1	CRC		33.2	3.9
11-2			34.9	4.6
11-3			36.6	4.5
12-1	CRC		30.6	5.1
12-2			31.3	5.5
12-3			29.3	5.8

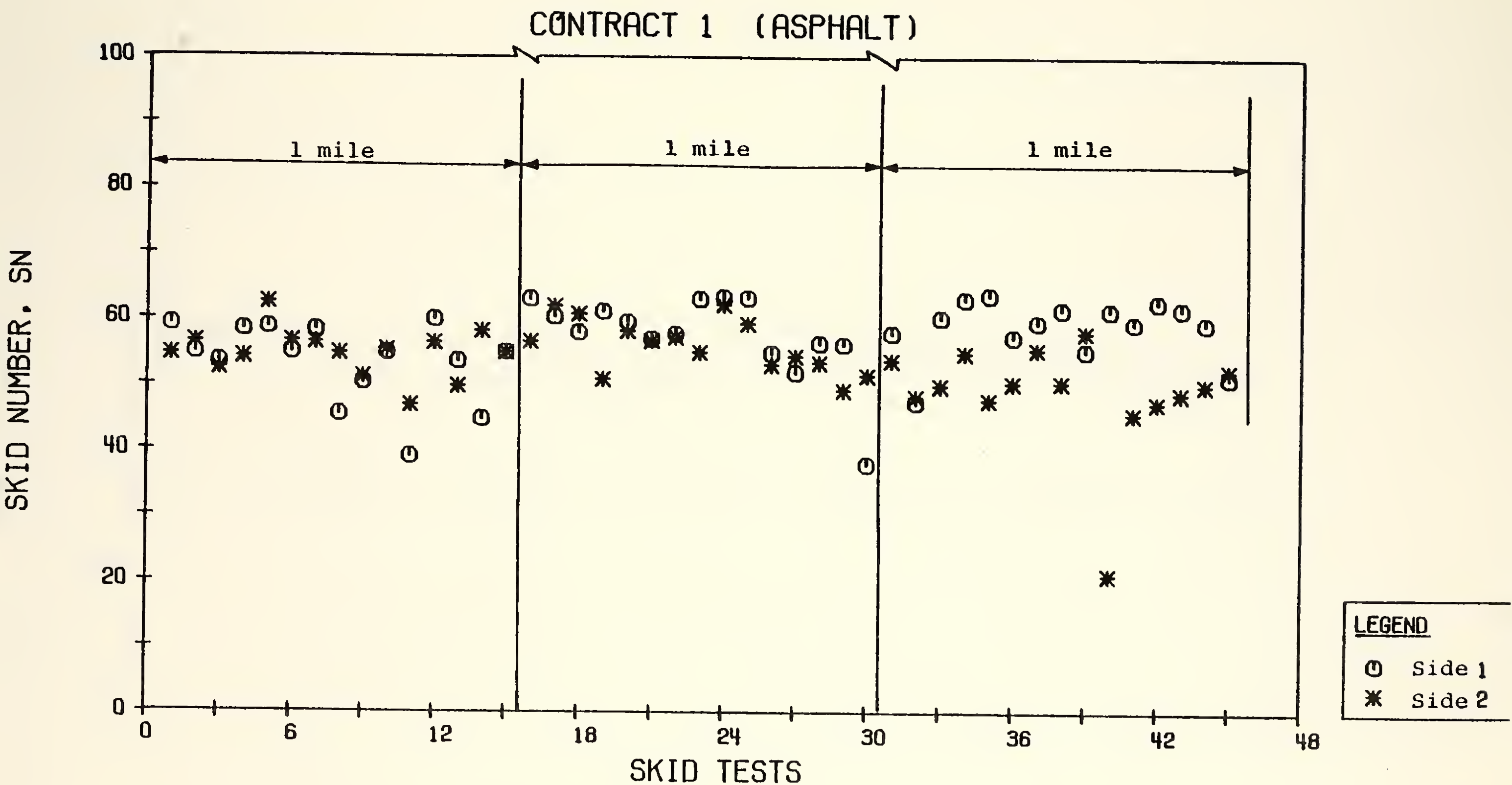

Figure E2. Variations in Skid Numbers Along Contract 1 (Asphalt)

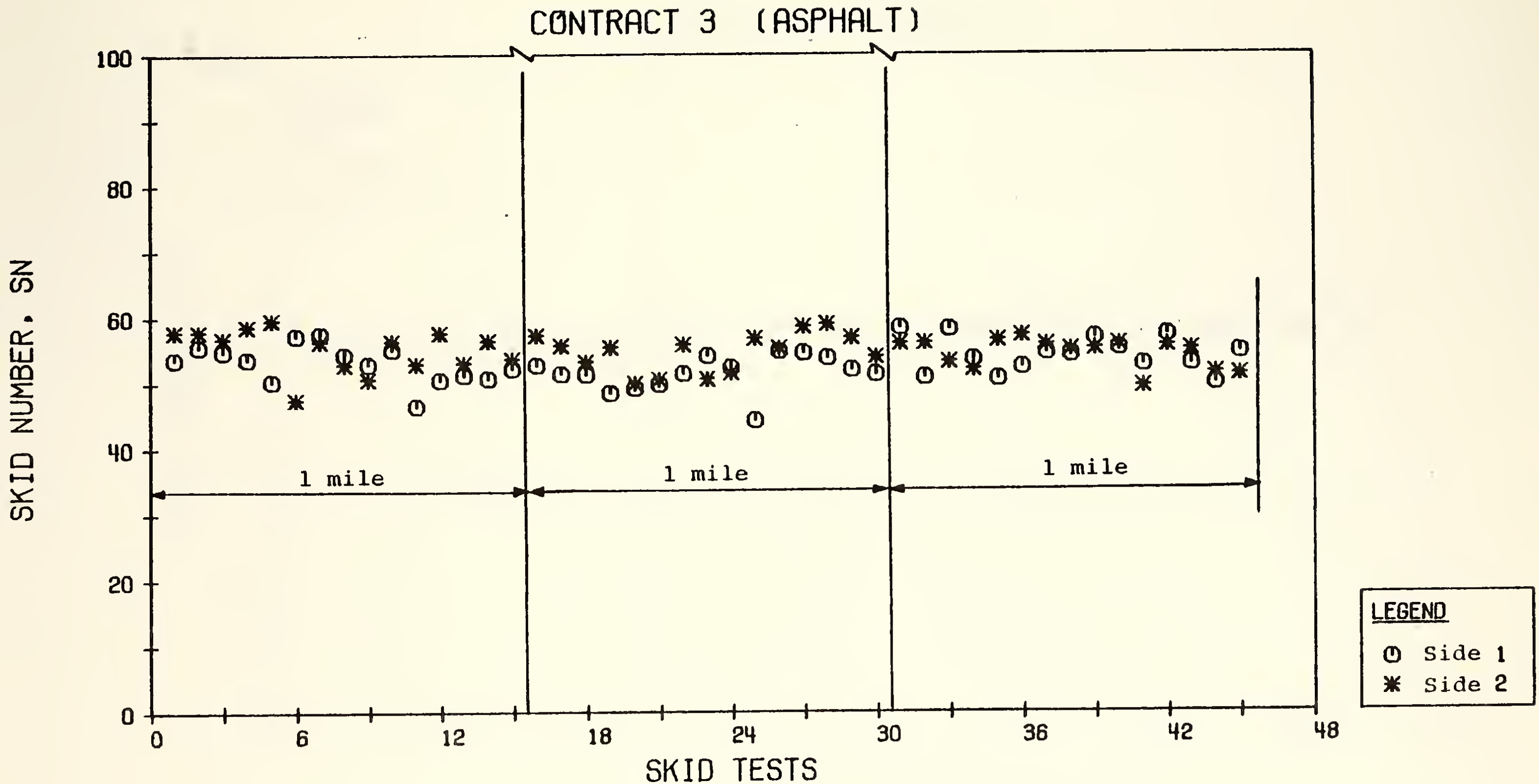

Figure E3. Variations in Skid Numbers Along Contract 3 (Asphalt)

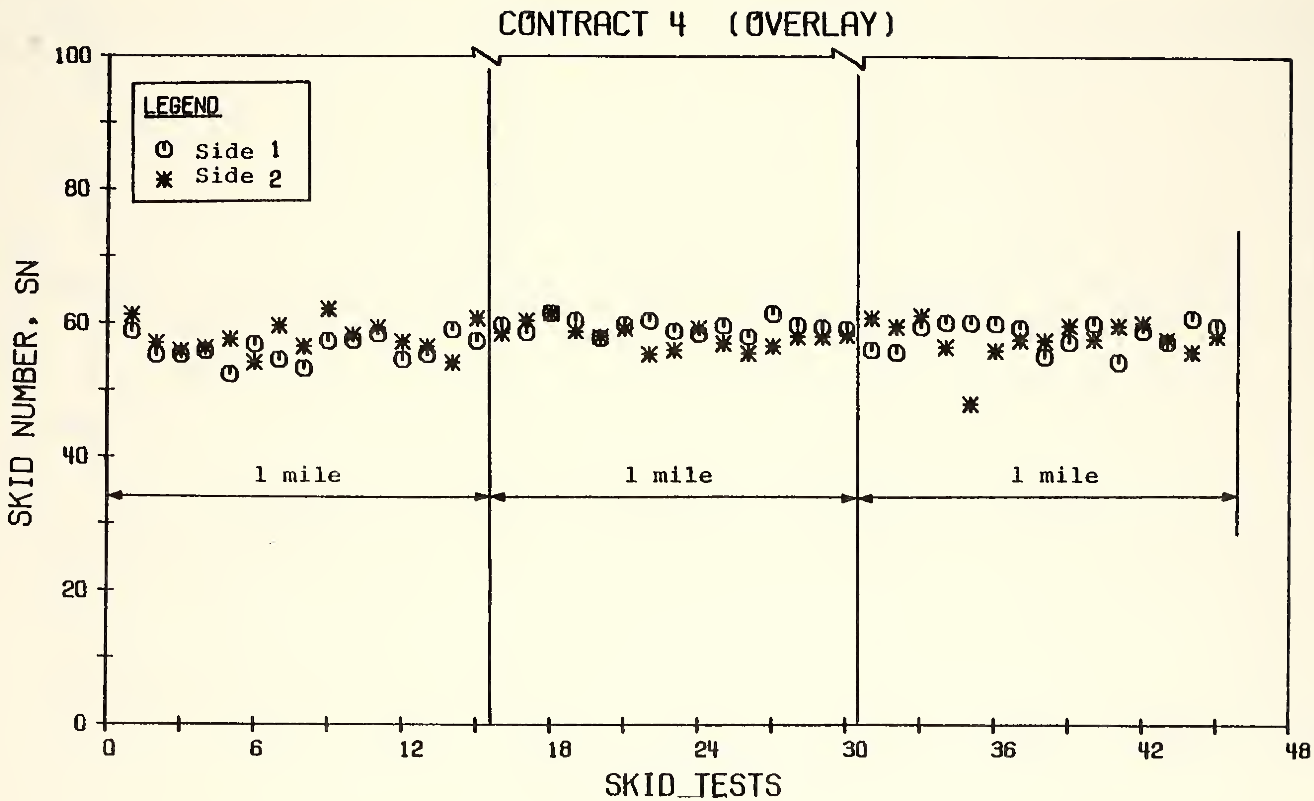

Figure E4. Variations in Skid Numbers Along Contract 4 (Overlay)

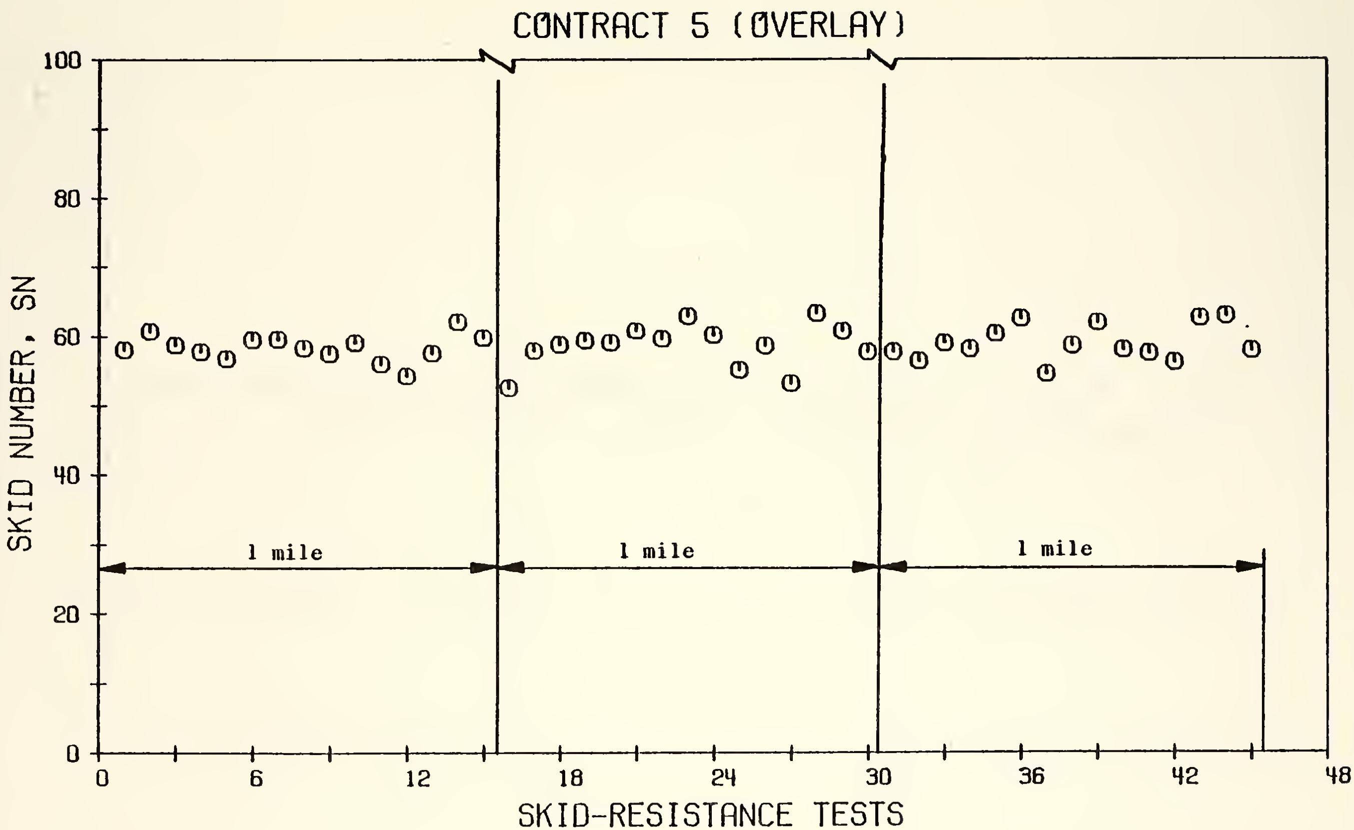

Figure E5. Variations in Skid Numbers Along Contract 5 (Overlay)

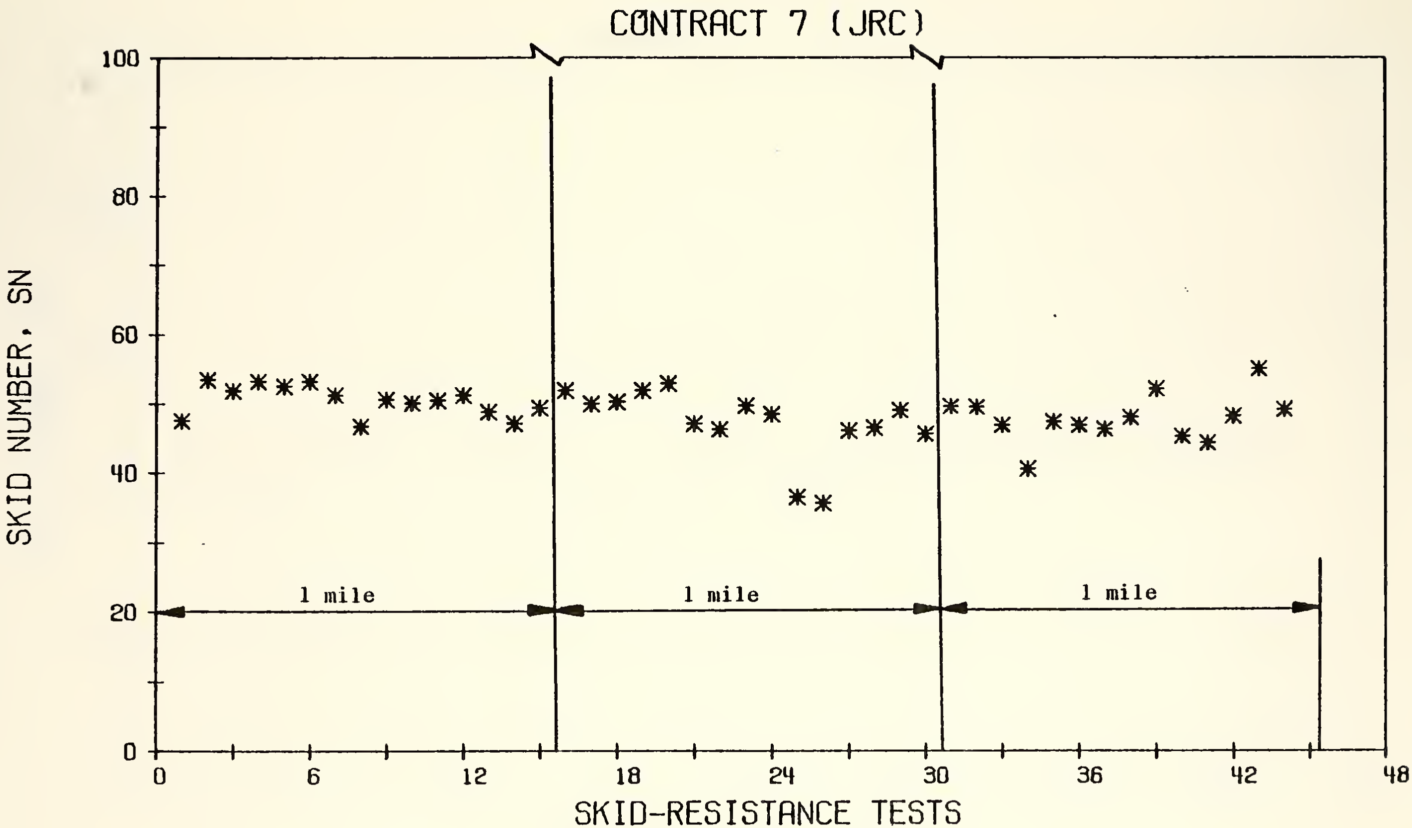

Figure E6. Variations in Skid Numbers Along Contract 7 (JRC)

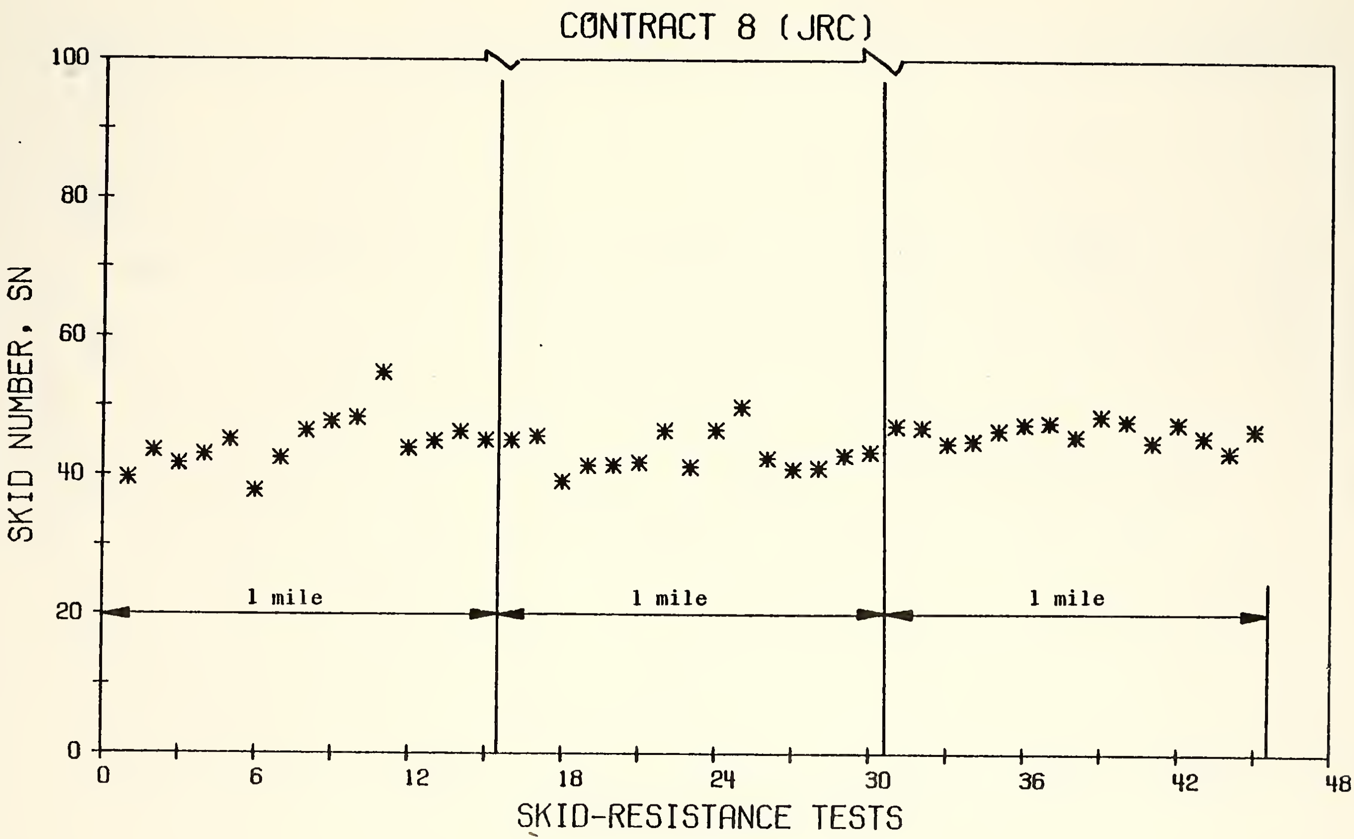

Figure E7. Variations in Skid Numbers Along Contract 8 (JRC)

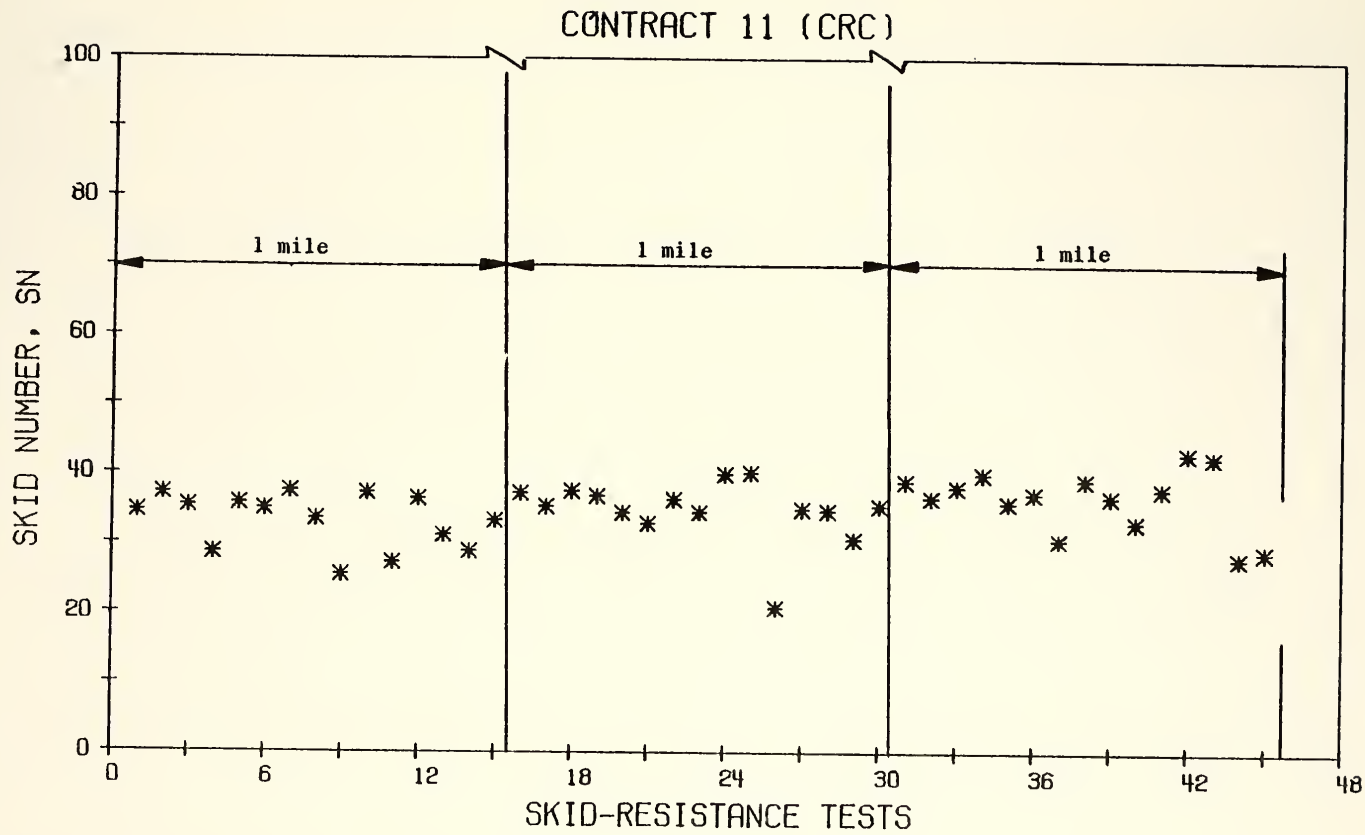

Figure E8. Variations in Skid Numbers Along Contract 11 (CRC)

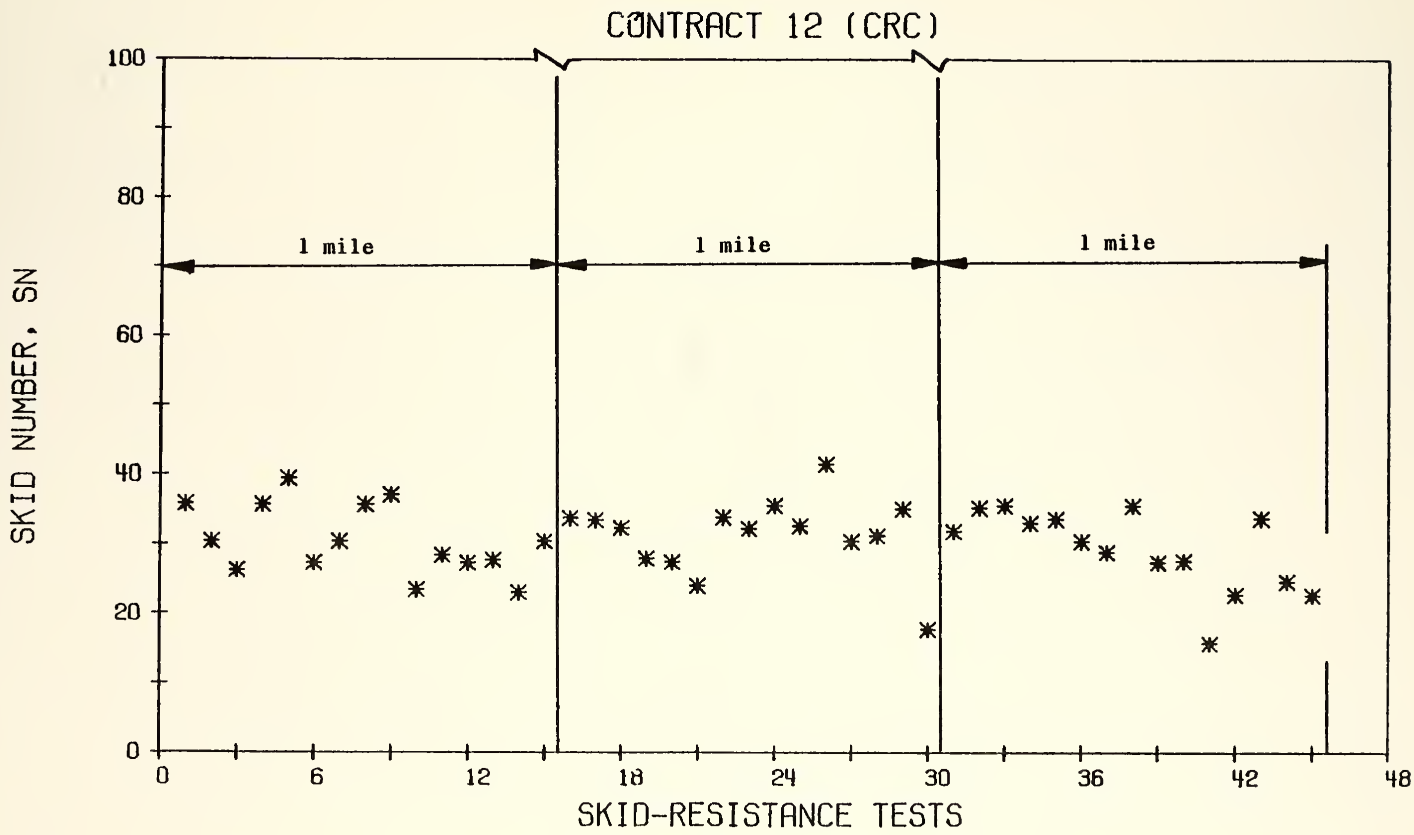

Figure E9 . Variations in Skid Numbers Along Contract 12 (CRC)

APPENDIX F

SEASONAL CHANGES IN PAVEMENT DEFLECTIONS

APPENDIX F

AN EXAMPLE OF THE STATISTICAL ANALYSIS FOR POOLING THE DATA FROM ILLINOIS AND MINNESOTA

May Data

(1) Full Model:

Analysis of Variance for Illinois Data

Source	dF	Sum Squares
Regression	1	16.82
Error	10	0.50

Analysis of Variance for Minnesota Data

Source	dF	Sum Squares
Regression	1	11.34
Error	10	7.83

(2) Reduced Model:

Analysis of Variance for Combined Data

Source	dF	Sum Squares
Regression	1	34.67
Error	22	8.57

$$F^* = \frac{\text{SSE(Reduced)} - \text{SSE(Full)}}{2} \div \frac{\text{SSE(Full)}}{20} = \frac{8.57-(0.5+7.82)}{2} \div \frac{8.32}{20}$$

$= 0.3 < 1$ Pool

TABLE F1. DEFLECTION DATA : (SEASONAL TESTING)

LOOP & SECTN	PAVE-MENT TYPE	DFLCTN PARA-METER	SEASON-YEAR F-77 AVG	F-77 SD	S-78 AVG	S-78 SD	F-79 AVG	F-79 SD	S-80 AVG	S-80 SD
1-5	ASPH	DMD	1.67	0.27	1.64	0.29	1.62	0.25	1.34	0.23
		SCI	0.55	0.12	0.46	0.13	0.61	0.15	0.45	0.18
		S5	0.40	0.04	0.48	0.07	0.39	0.09	0.36	0.03
		SPD	53.2	2.30	58.8	3.10	53.6	2.90	53.6	4.30
1-12	ASPH	DMD	2.85	0.80	3.50	0.94	2.82	0.92	3.33	1.20
		SCI	0.59	0.16	0.89	0.21	0.51	0.32	1.33	0.85
		S5	0.65	0.09	0.68	0.07	0.81	0.30	0.50	0.07
		SPD	57.9	2.40	53.9	1.90	60.0	6.10	46.8	4.30
1-20	ASPH	DMD	1.75	0.23	3.03	0.48	1.94	0.24	1.66	0.41
		SCI	0.34	0.09	0.77	0.18	0.35	0.18	0.61	0.20
		S5	0.37	0.08	0.43	0.15	0.54	0.13	0.21	0.07
		SPD	58.1	3.40	51.4	4.30	59.0	3.10	46.9	3.40
4-1	ASPH	DMD	2.04	0.43	2.76	0.46	1.10	0.42	1.58	0.32
		SCI	0.66	0.15	0.82	0.13	0.46	0.37	0.65	0.16
		S5	0.25	0.05	0.32	0.09	0.11	0.03	0.16	0.04
		SPD	47.5	1.90	41.2	2.20	45.3	4.10	43.4	2.10
5-7	ASPH	DMD	0.89	0.12	2.00	0.19	0.39	0.05	0.77	0.15
		SCI	0.29	0.05	0.34	0.09	0.13	0.02	0.26	0.06
		S5	0.22	0.04	0.31	0.06	0.11	0.02	0.21	0.04
		SPD	53.8	3.50	56.3	4.50	56.9	3.80	54.1	3.40
5-8	ASPH	DMD	1.04	0.14	1.14	0.20	0.44	0.05	0.60	0.12
		SCI	0.32	0.09	0.32	0.12	0.15	0.04	0.26	0.10
		S5	0.22	0.02	0.30	0.03	0.10	0.01	0.19	0.04
		SPD	52.4	3.50	56.5	4.40	33.8	3.60	53.4	4.80
5-10	ASPH	DMD	2.04	0.31	1.64	0.45	0.96	0.18	2.00	0.39
		SCI	0.55	0.12	0.36	0.09	0.26	0.08	0.59	0.18
		S5	0.46	0.12	0.45	0.13	0.25	0.03	0.69	0.74
		SPD	55.3	3.90	60.6	3.40	58.3	3.40	57.2	10.9
5-11	ASPH	DMD	1.25	0.16	2.50	0.28	0.58	0.08	1.78	0.23
		SCI	0.17	0.05	0.49	0.05	0.11	0.02	0.40	0.12
		S5	0.50	0.10	0.71	0.11	0.23	0.04	0.68	0.64
		SPD	69.6	2.40	62.0	2.50	68.1	1.40	60.8	7.60
5-14	ASPH	DMD	1.16	0.13	1.89	0.22	0.60	0.08	1.16	0.93
		SCI	0.24	0.07	0.52	0.11	0.19	0.07	0.68	0.89
		S5	0.33	0.05	0.44	0.09	0.15	0.02	0.27	0.04
		SPD	60.2	3.30	55.3	3.00	56.4	4.20	48.5	5.30
2-6 *	ASPH	DMD	1.67	0.30	2.33	0.34	0.86	0.24	1.16	0.22
		SCI	0.69	0.19	1.01	0.27	0.18	0.09	0.35	0.14
		S5	0.16	0.07	0.25	0.09	0.27	0.16	0.33	0.06
		SPD	42.9	4.00	42.7	4.50	61.4	8.20	50.1	4.10
5-15*	ASPH	DMD	3.30	1.52	3.49	1.47	0.74	0.22	2.07	0.60
		SCI	1.30	0.77	1.42	0.80	0.18	0.11	0.69	0.26
		S5	0.29	0.08	0.29	0.10	0.17	0.05	0.20	0.07
		SPD	44.4	4.80	43.5	5.00	59.4	7.60	47.1	5.10
5-17*	ASPH	DMD	2.86	0.52	3.59	0.68	0.81	0.14	2.42	1.27
		SCI	1.15	0.37	1.47	0.49	0.24	0.05	1.05	1.33
		S5	0.15	0.07	0.22	0.04	0.14	0.02	0.24	0.10
		SPD	42.8	3.90	40.2	3.40	52.8	2.80	44.8	5.30

* RECEIVED ASPHALT OVERLAYS

TABLE F1.(CONTINUED)

LOOP & SECTN	PAVE-MENT TYPE	DFLCTN PARA-METER	SEASON-YEAR F-77 AVG	SD	S-78 AVG	SD	F-78 AVG	SD	F-79 AVG	SD	S-80 AVG	SD
1-9	OVLY	DMD	0.97	.13	1.02	.23			0.71	.05	0.96	.23
		SCI	0.10	.05	0.09	.10			0.10	.04	0.23	.12
		S5	0.43	.12	0.47	.13			0.33	.03	0.37	.10
		SPD	71.4	3.9	76.6	8.4			73.8	3.3	64.2	6.7
3-3	OVLY	DMD	0.88	.20	1.09	.22			0.28	.04	0.64	.22
		SCI	0.16	.10	0.18	.07			0.06	.02	0.13	.24
		S5	0.28	.09	0.42	.12			0.11	.02	1.14	
		SPD	65.7	8.3	69.5	5.5			68.1	5.3		
4-10	OVLY	DMD	0.72	.11	0.86	.14	0.68	.14	0.28	.06	0.71	.04
		SCI	0.08	.04	0.10	.04	0.11	.05	0.04	.03	0.05	.04
		S5	0.33	.07	0.43	.07	0.29	.05	0.14	.03	0.25	.03
		SPD	73.6	5.5	76.7	2.7	70.7	4.4	75.9	6.1	66.2	3.1
4-13	OVLY	DMD	0.84	.15	0.89	.12	0.72	.13	0.27	.08	0.76	.26
		SCI	0.08	.07	0.10	.21	0.11	.10	0.04	.07	0.05	.14
		S5	0.33	.11	0.43	.08	0.29	.05	0.14	.02	0.25	.07
		SPD	71.9	7.6	71.2	7.4	65.6	6.8	70.8	10.	63.2	7.3
5-18	OVLY	DMD	0.74	.09	0.95	.11	0.65	.09	0.32	.05	0.66	.06
		SCI	0.09	.02	0.07	.05	0.05	.03	0.06	.02	0.13	.07
		S5	0.37	.08	0.53	.10	0.30	.06	0.15	.04	0.24	.04
		SPD	74.8	3.9	79.5	4.0	75.3	4.3	72.8	3.9	62.9	
1-6	JRC	DMD	0.69	.07	0.77	.05			0.67	.03	0.77	.29
		SCI	.053	.06	.024	.01			.055	.03	.162	.27
		S5	0.37	.02	0.48	.03			0.37	.02	0.37	.04
		SPD	78.4	4.6	84.5	2.1			78.6	1.9	71.7	9.2
1-14	JRC	DMD	0.76	.20	0.65	.10			0.66	.06	1.02	.48
		SCI	.044	.06	.054	.02			.103	.05	.496	.44
		S5	0.40	.06	0.38	.09			0.33	.07	0.29	.08
		SPD	76.5	3.9	80.9	3.7			73.0	6.3	56.1	14.
1-16	JRC	DMD	0.61	.13	0.74	.24	0.59	.23	0.62	.05	0.51	.07
		SCI	.048	.06	.031	.02	.094	.16	.114	.05	.078	.05
		S5	0.27	.03	0.42	.05	0.27	.03	0.29	.04	0.26	.03
		SPD	75.1	5.8	81.0	5.1	75.1	7.6	72.4	3.6	73.7	5.9
1-17	JRC	DMD	0.72	.18	0.76	.09	0.56	.10	0.65	.05	0.61	.13
		SCI	.079	.09	.041	.02	.033	.03	.162	.04	.086	.06
		S5	0.34	.05	0.43	.06	0.28	.03	0.29	.04	0.29	.04
		SPD	74.6	6.1	80.8	2.6	77.2	4.8	65.7	3.2	72.6	5.5
4-3	JRC	DMD	0.42	.09	0.61	.11	0.41	.07	0.19	.03	0.43	.05
		SCI	.019	.01	.029	.01	.031	.01	.010	.01	.050	.04
		S5	0.25	.06	0.38	.09	0.25	.05	0.11	.02	0.23	.04
		SPD	81.1	3.4	79.7	2.3	81.5	3.7	80.7	4.0	74.7	5.2
5-20	JRC	DMD	0.71	.08	0.84	.09	0.94	.49	0.28	.05	0.80	.34
		SCI	.039	.03	.019	.02	.119	.14	.031	.02	.165	.32
		S5	0.40	.04	0.51	.08	0.43	.11	0.15	.02	0.21	.03
		SPD	80.7	3.3	83.7	3.7	76.5	7.3	79.1	5.8		
1-1	CRC	DMD	0.48	.06	0.51	.04	0.51	.09	0.37	.09	0.37	.08
		SCI	.033	.02	.034	.01	.054	.03	.067	.06	.065	.02
		S5	0.21	.02	0.27	.02	0.25	.04	0.22	.08	0.20	.04
		SPD	72.9	3.3	78.9	1.5	75.2	5.1	76.6	10.	73.3	3.2
1-2	CRC	DMD	0.68	.14	0.63	.06	0.55	.09	0.49	.07	0.51	.12
		SCI	.039	.05	.042	.01	.062	.04	.049	.03	.120	.10
		S5	0.28	.03	0.36	.03	0.28	.03	0.23	.02	0.25	.05
		SPD	73.5	4.3	79.3	2.3	75.3	5.5	71.2	5.2	70.5	6.8
2-8	CRC	DMD	0.31	.03	0.52	.05			0.16	.01	0.37	.01
		SCI	.040	.02	.042	.01			.021	.01	.060	.05
		S5	0.12	.01	0.24	.02			0.07	.01	0.16	.02
		SPD	71.3	4.8	75.0	1.2			74.8	2.7	69.2	6.9

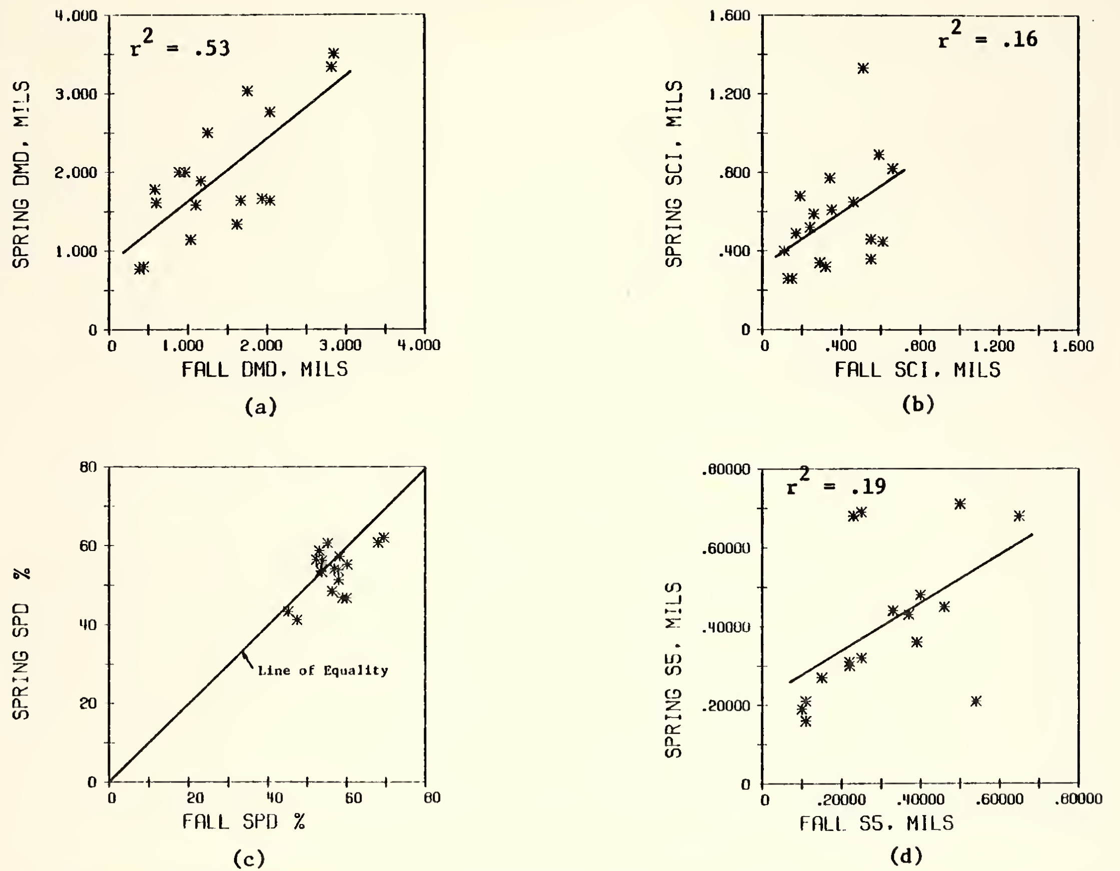

Figure F1. Spring-Fall Relationship for the Deflection Parameters of Asphalt Pavement Test Sections: (a) DMD; (b) SCI; (c) SPD; (d) S_5

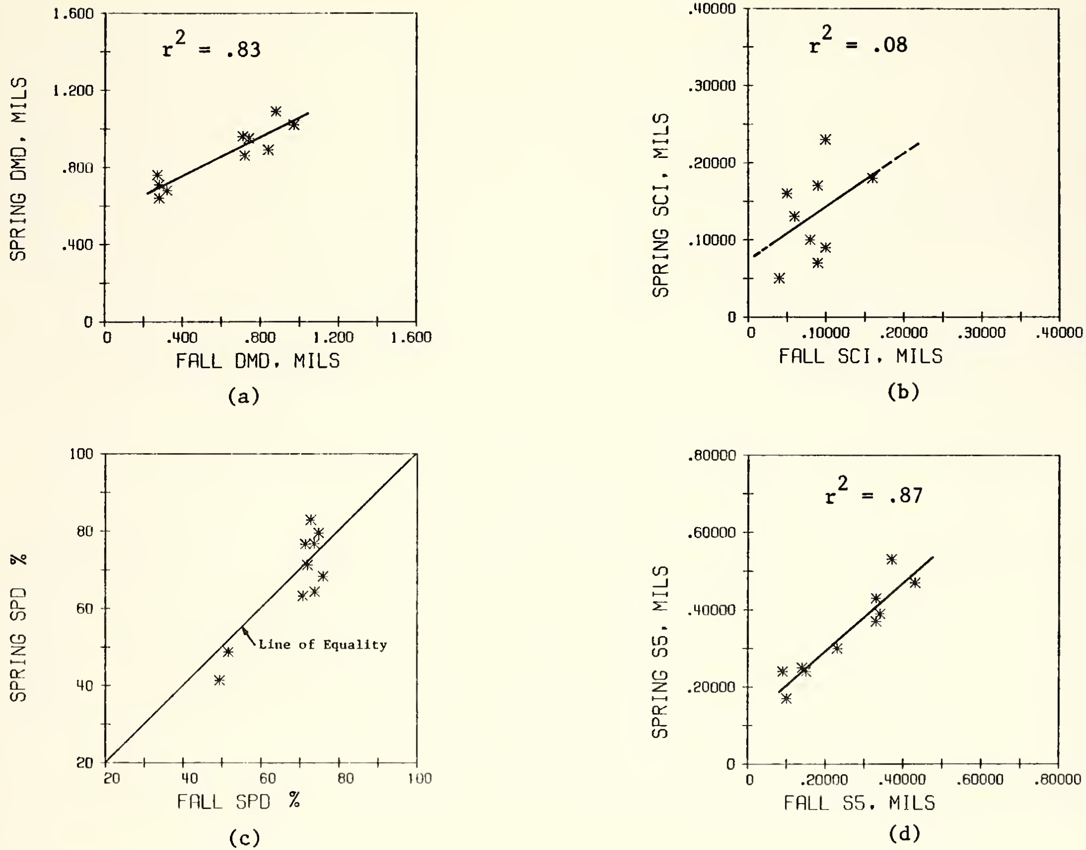

Figure F2. Spring-Fall Relationship for the Deflection Parameters of Overlay Pavement Test Sections: (a) DMD; (b) SCI; (c) SPD; (d) S_5

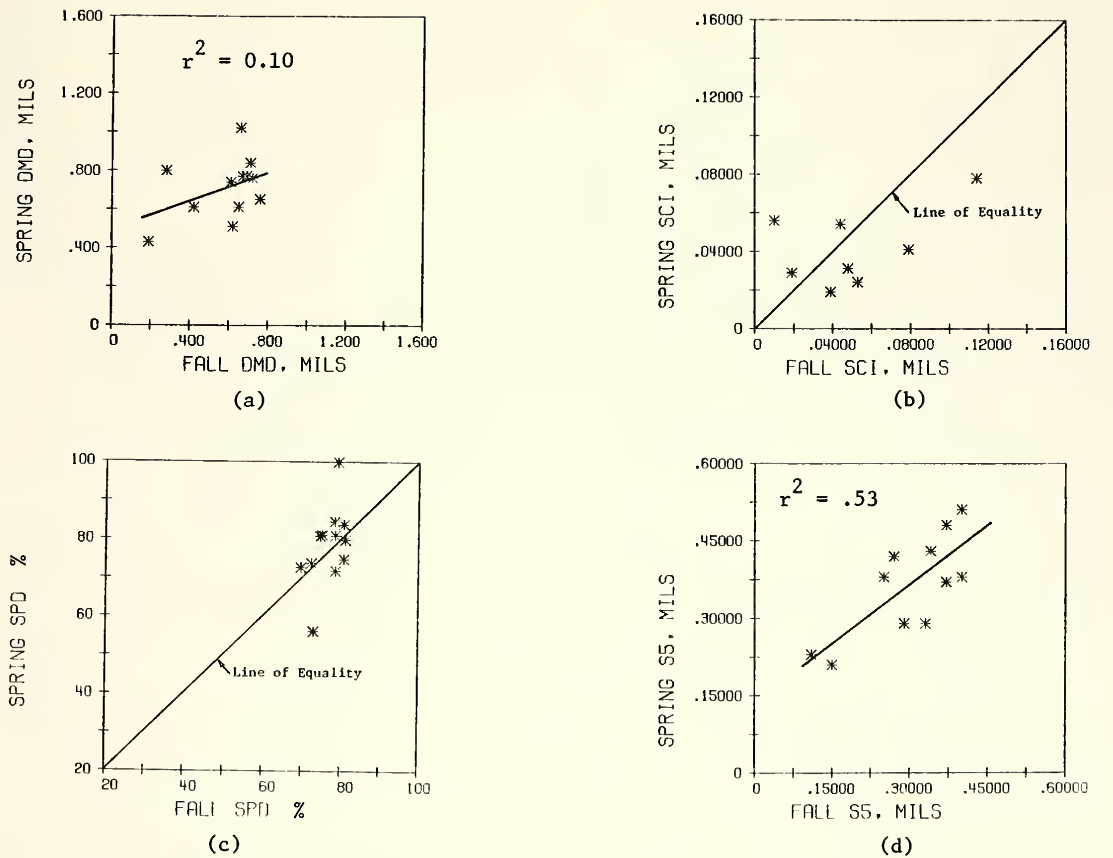

Figure F3. Spring-Fall Relationship for the Deflection Parameters of JRC Pavement Test Sections: (a) DMD; (b) SCI; (c) SPD; (d) S_5

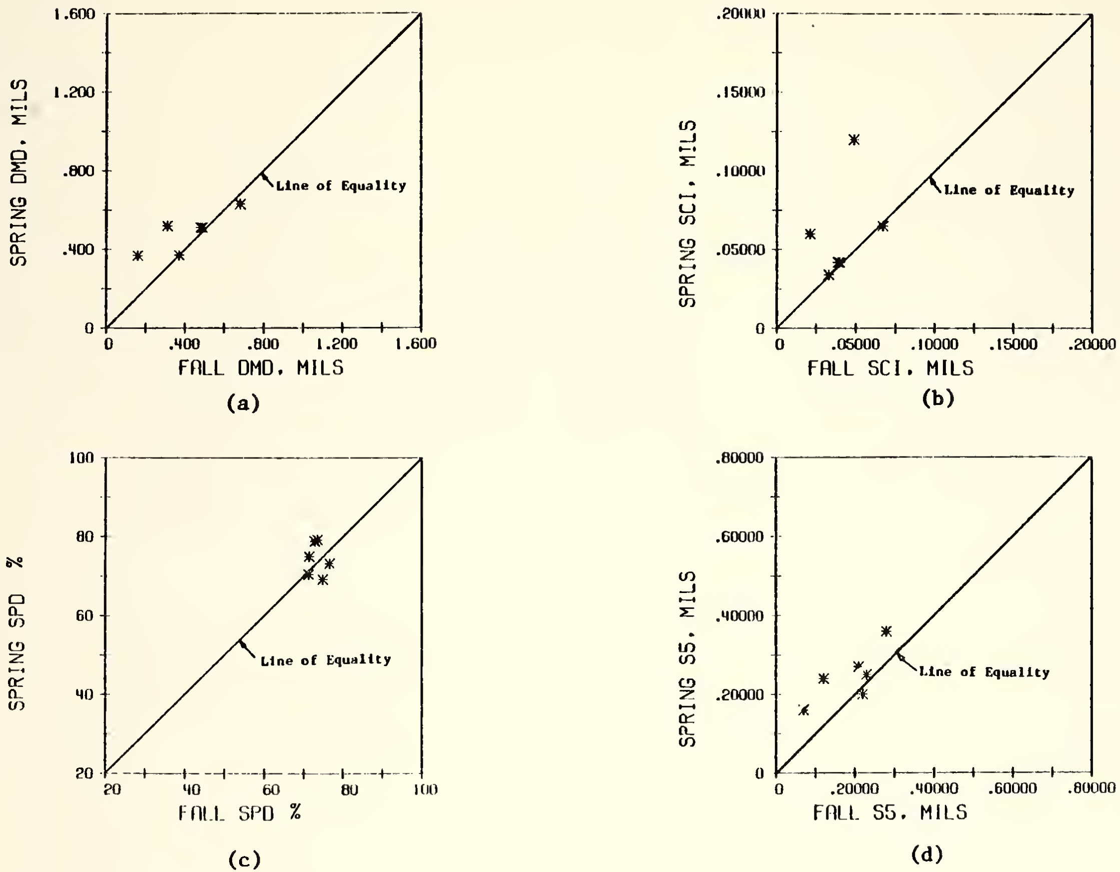

Figure F4. Spring-Fall Relationship for the Deflection Parameters of CRC Pavement Test Sections: (a) DMD; (b) SCI; (c) SPD; (d) S_5

APPENDIX G

VARIABILITY OF PAVEMENT DEFLECTIONS OVER CONTRACT SECTIONS

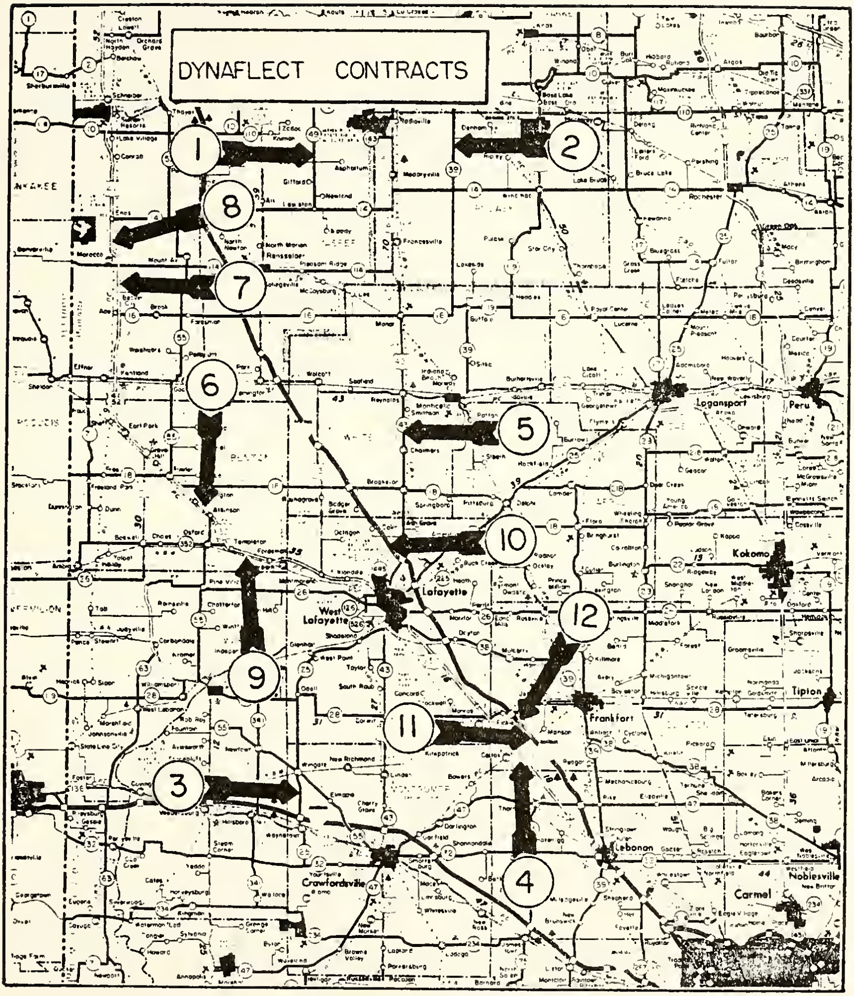

Figure G1. Test Contracts for Deflection Variability Study

TABLE G1. GEOGRAPHIC LOCATIONS OF DEFLECTION VARIABILITY STUDY CONTRACTS.

CONTRACT	PVMT	HIGHWAY	DRCTN	GEOGRAPHIC LOCATION
1	ASPH	SR-49	NBL	0.5 FROM JCT. SR-49/SR-14
2	ASPH	SR-39	NBL	0.7 FROM JCT. SR-14 E
3	ASPH	SR-25	SBL	1.1 FROM JCT. SR-35
4	OVLY	US-52	WBL	1.0 FROM BOONE-CLNTN CO.LINE
5	OVLY	SR-43	NBL	5.6 FROM JCT. SR-18 W
6	OVLY	US-52	EBL	0.3 FROM JCT. SR-18 E
7	JRCP	US-41	SBL	0.1 FROM SR-114
8	JRCP	US-41	NBL	2.2 FROM JCT. SR-114
9	JRCP	US-52	WBL	1.4 FROM BNTN-TPCNOE CO.LINE
10	CRCP	I-65	SBL	7.0 FROM SR-18
11	CRCP	I-65	SBL	0.7 FROM SR-28
12	CRCP	I-65	NBL	2.1 FROM BOONE-CLNTN CO.LINE

TABLE C2. SUMMARY OF ANALYSES ON BASIN PARAMETERS (N=10)

PAVEMENT	PARAMETER	POSITION	ERROR	PARAMETER
ASPALT	SCI		.031	.432
	BCI		.011	.094
	SPD		1.00	49.2
OVERLAY	SCI	CRACK	.019	.194
		M-S	.016	.129
	BCI	CRACK	.019	.236
		M-S	.017	.214
	SPD	CRACK	1.40	66.9
		M-S	1.00	72.3
JRC	SCI	JOINT	.011	.104
		M-S	.008	.059
	BCI	JOINT	.010	.129
		M-S	.007	.133
	SPD	JOINT	1.00	70.0
		M-S	1.00	77.0
CRC	SCI		.003	.046
	BCI		.035	.078
	SPD		1.00	73.5

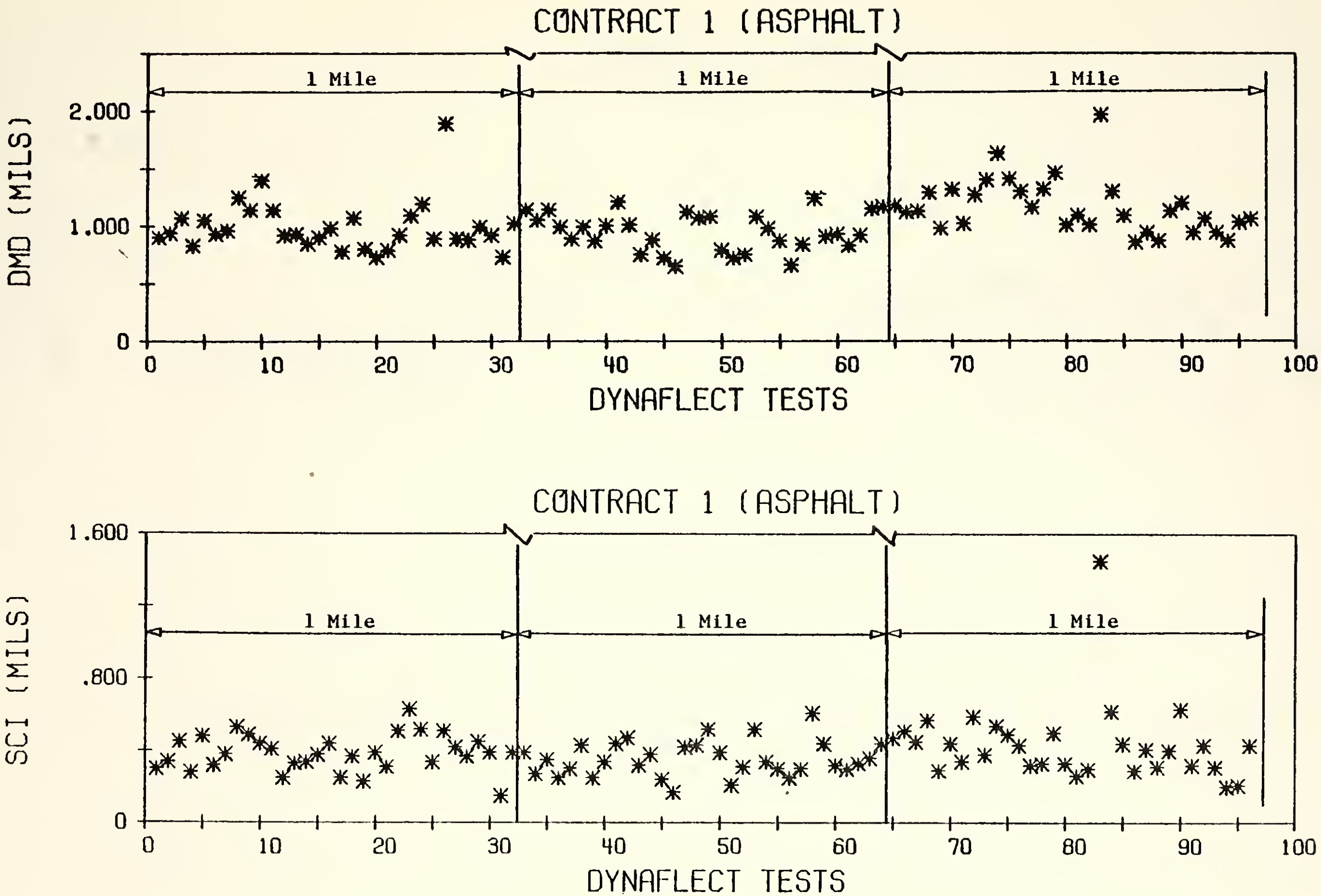

Figure G2. Variations of DMD and SCI Along Contract 1 (Asphalt)

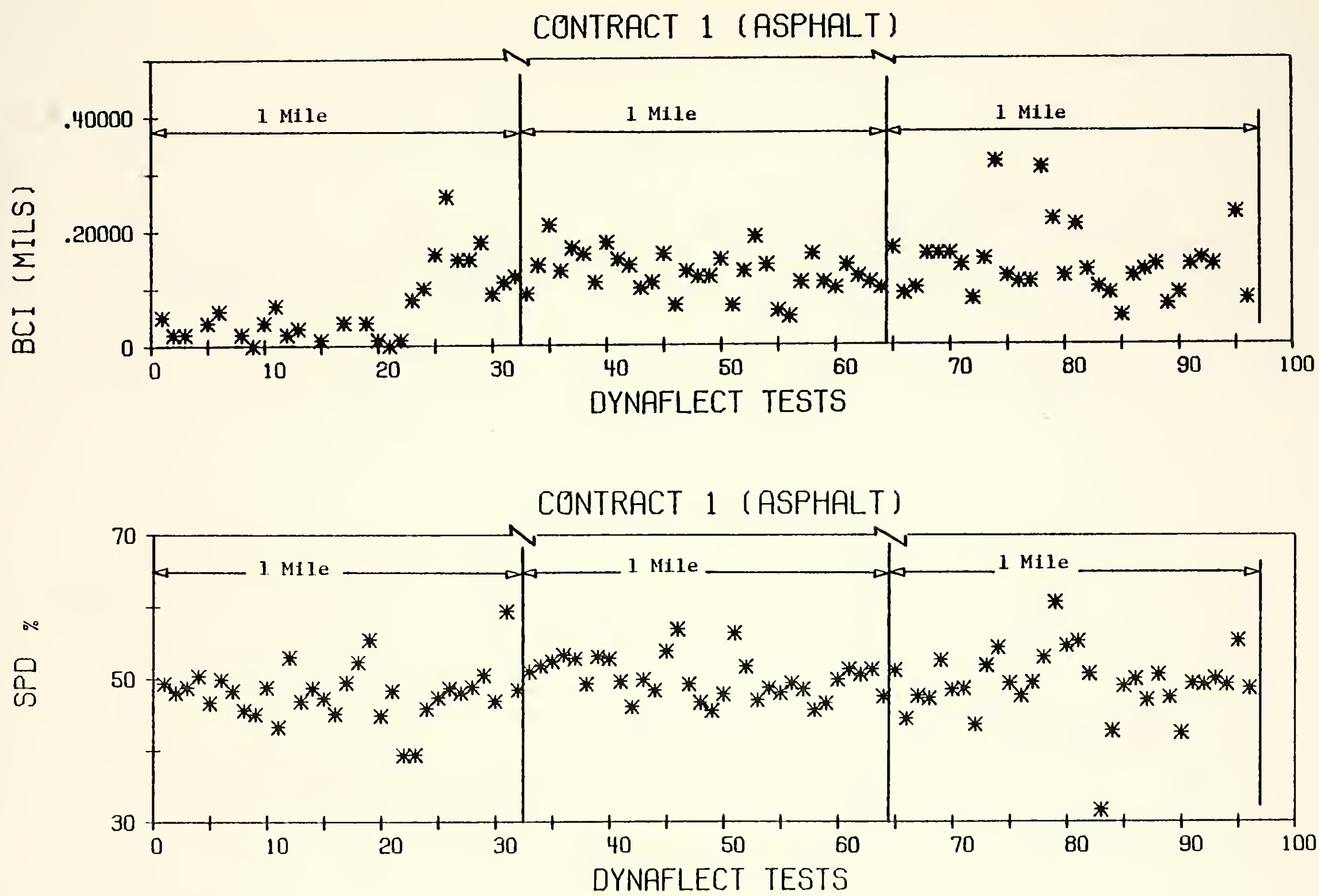

Figure C3. Variations of BCI and SPD Along Contract 1 (Asphalt)

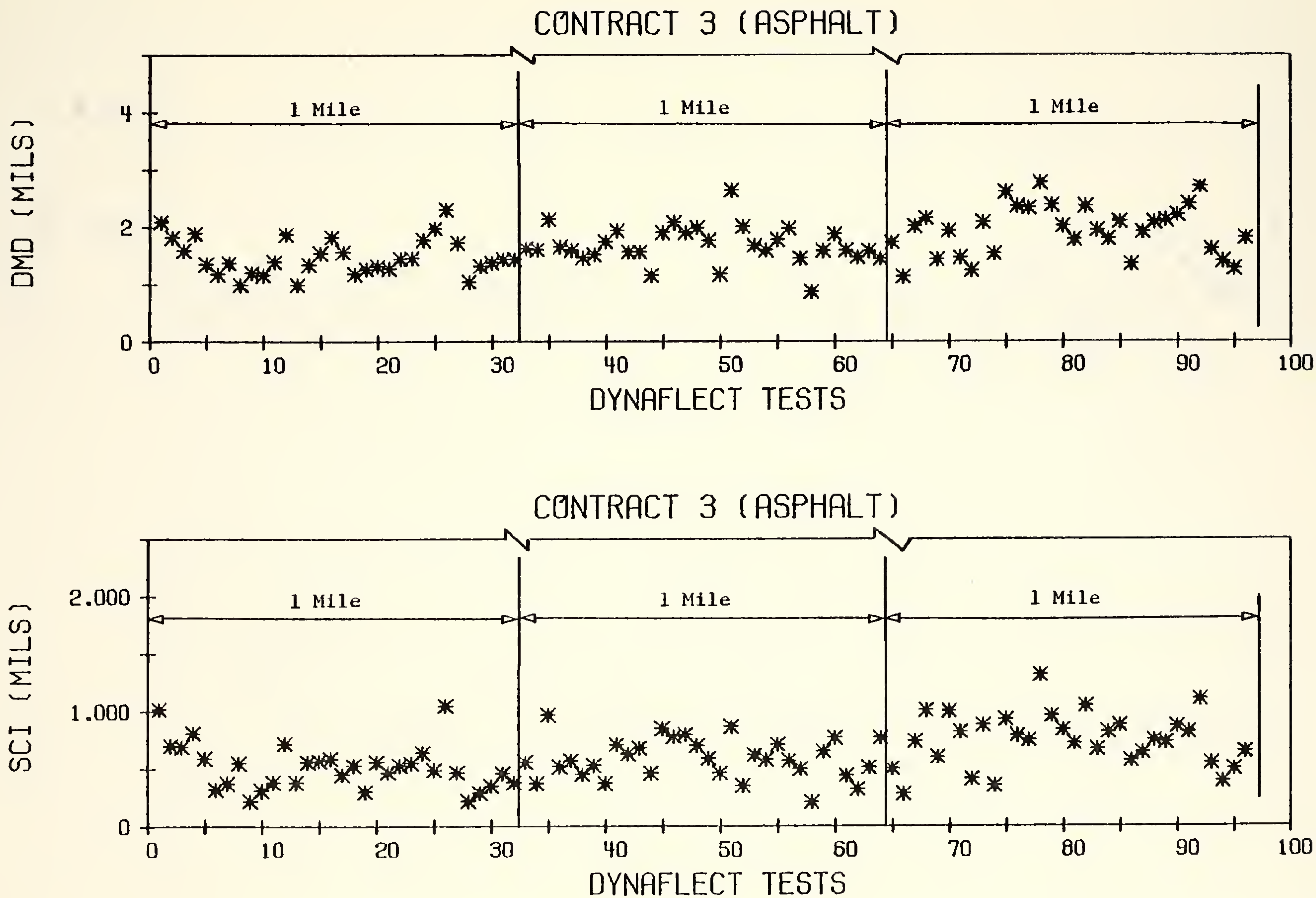

Figure G4. Variations of DMD and SCI Along Contract 3 (Asphalt)

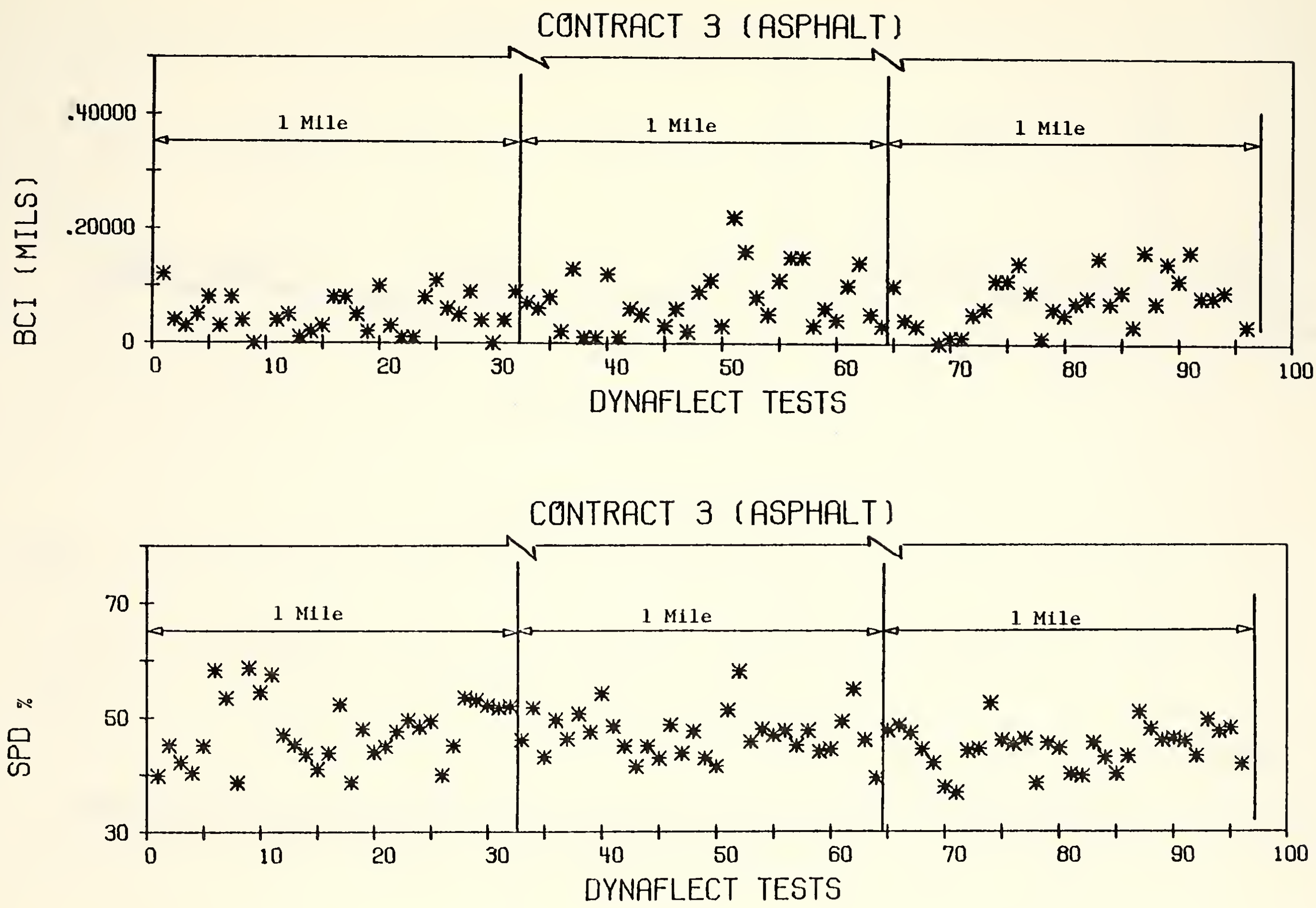

Figure G5. Variations of BCI and SPD Along Contract 3 (Asphalt)

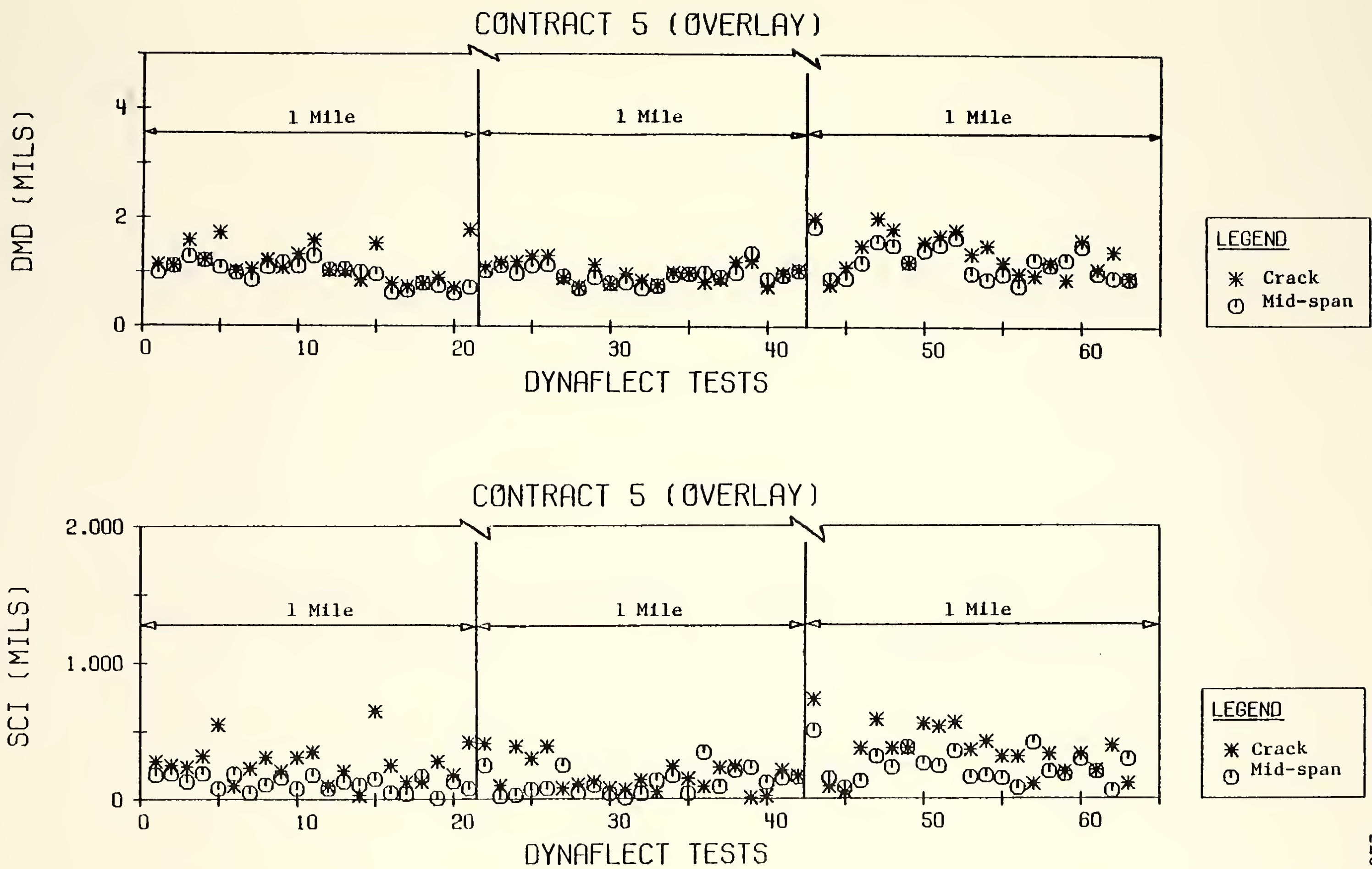

Figure C6. Variations of DMD and SCI Along Contract 5 (Overlay)

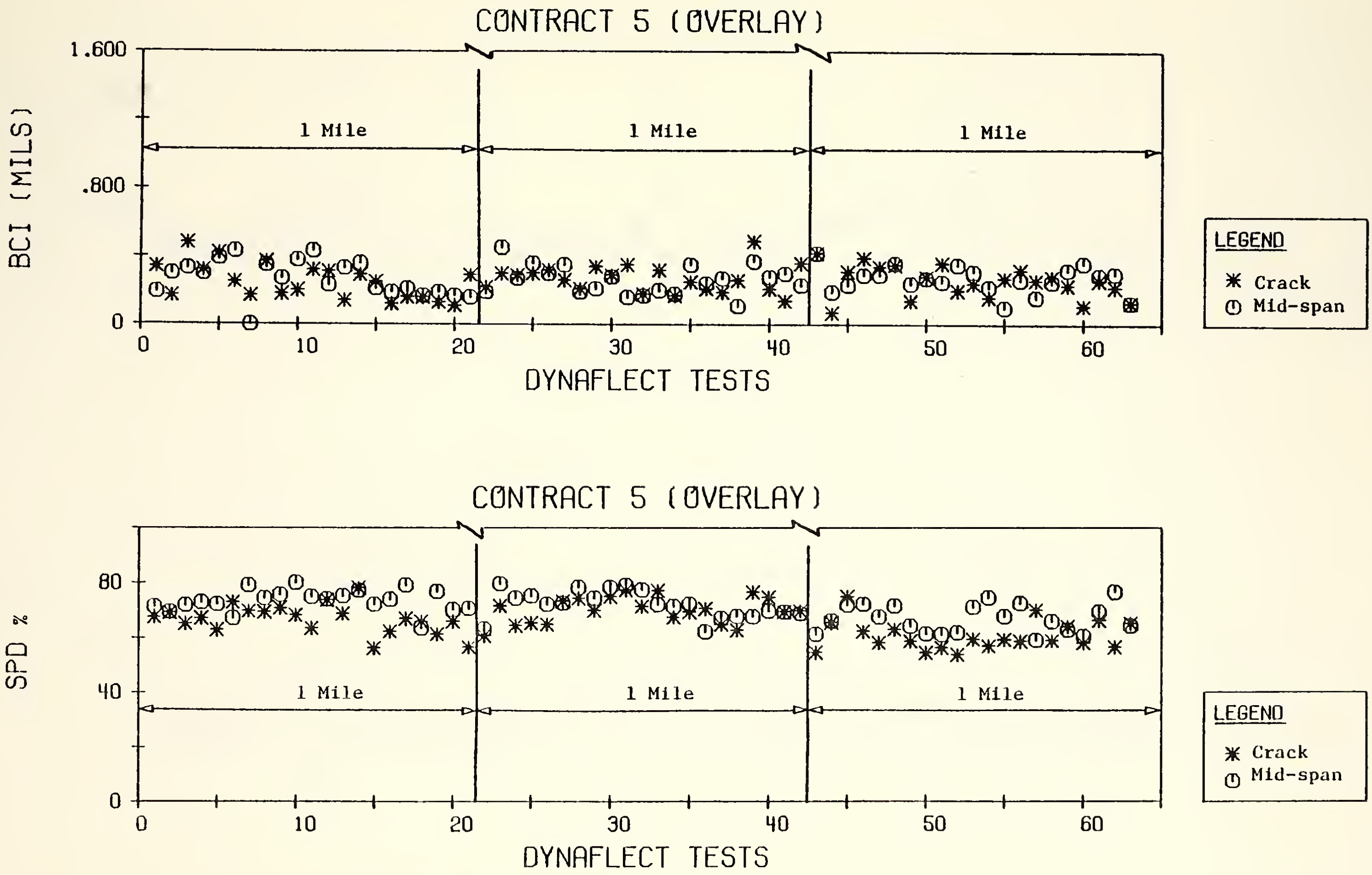

Figure G7. Variations of BCI and SPD Along Contract 5 (Overlay)

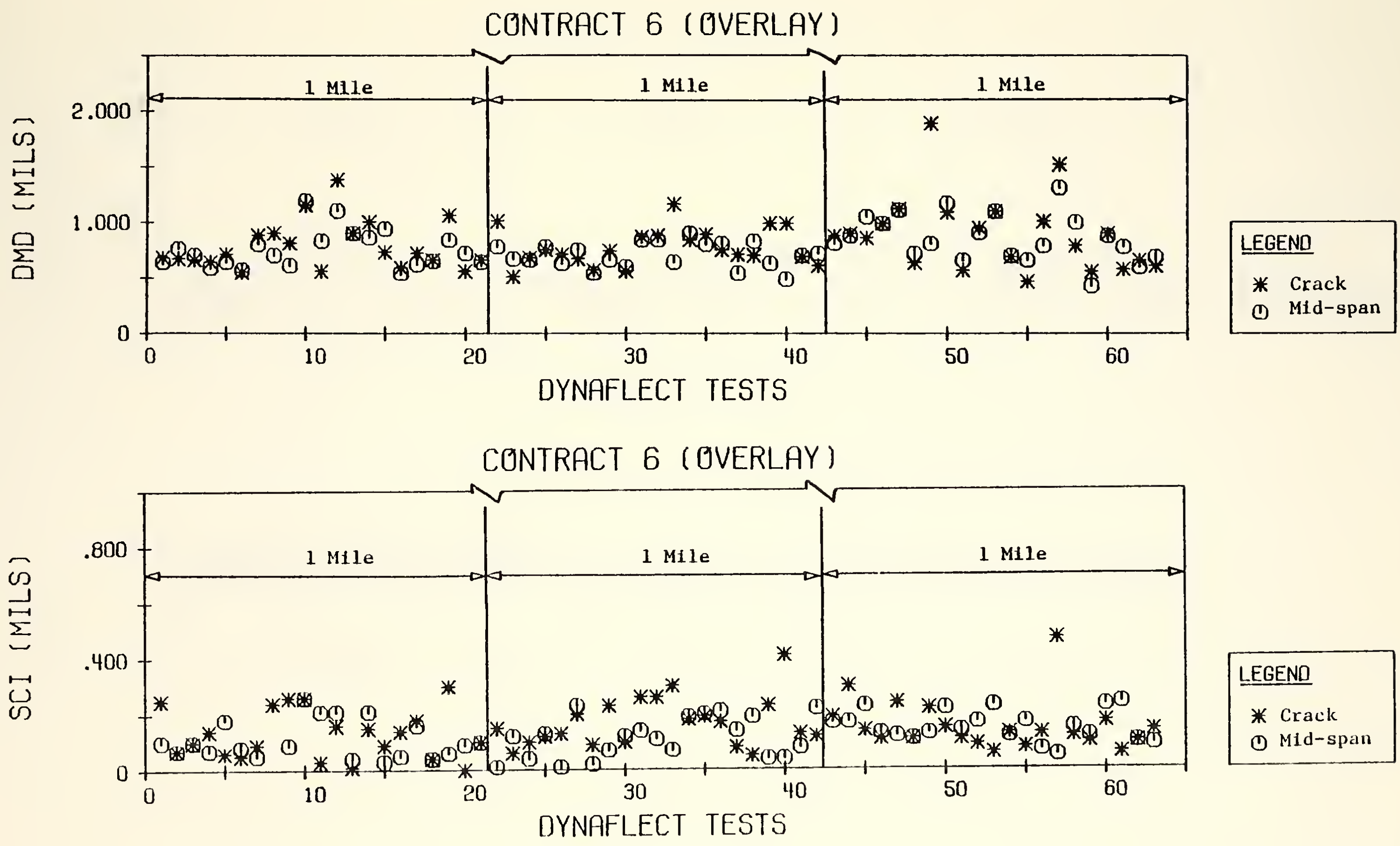

Figure G8. Variations of DMD and SCI Along Contract 6 (Overlay)

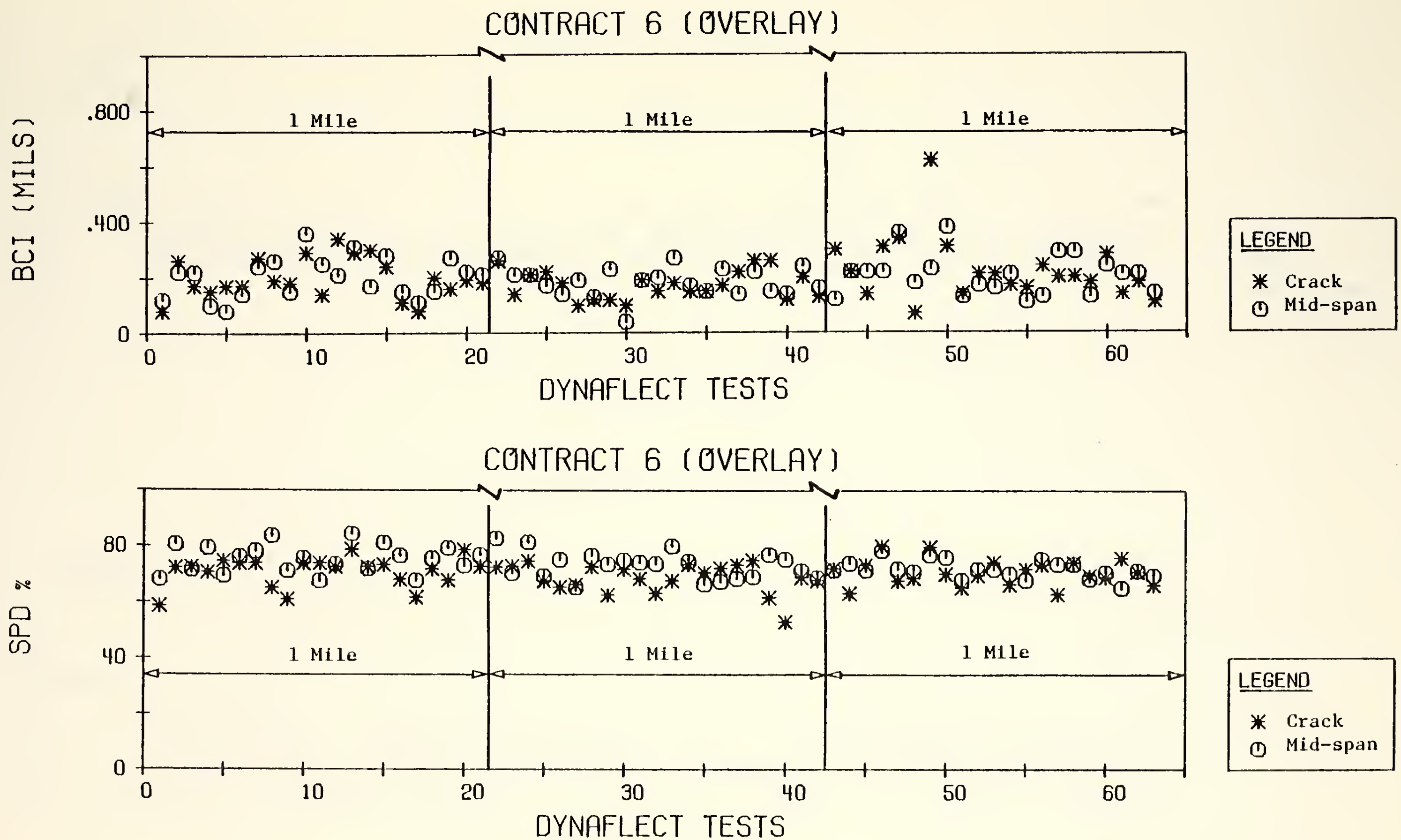

Figure C9. Variations of BCI and SPD Along Contract 6 (Overlay)

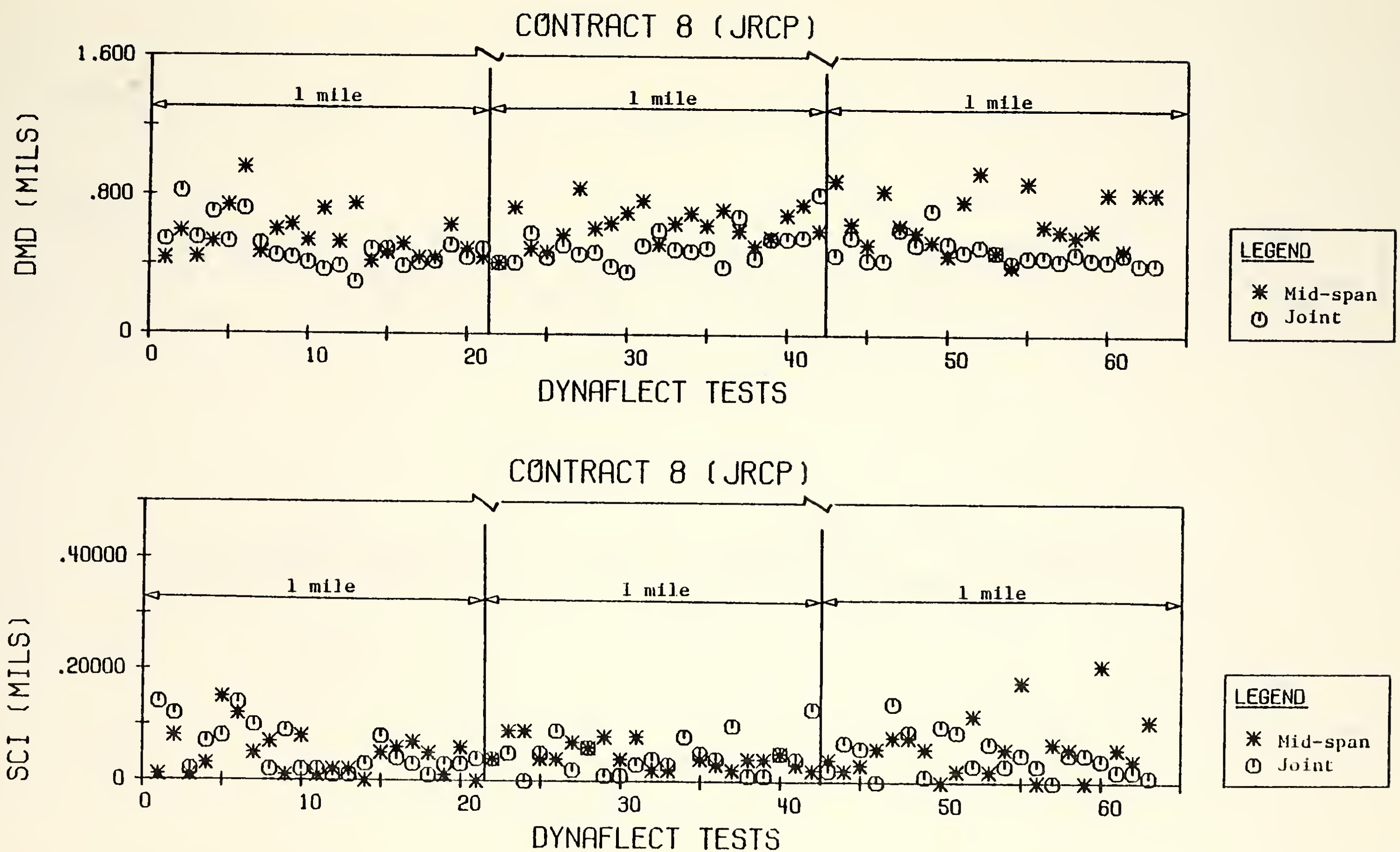

Figure G10. Variations of DMD and SCI Along Contract 8 (JRCP)

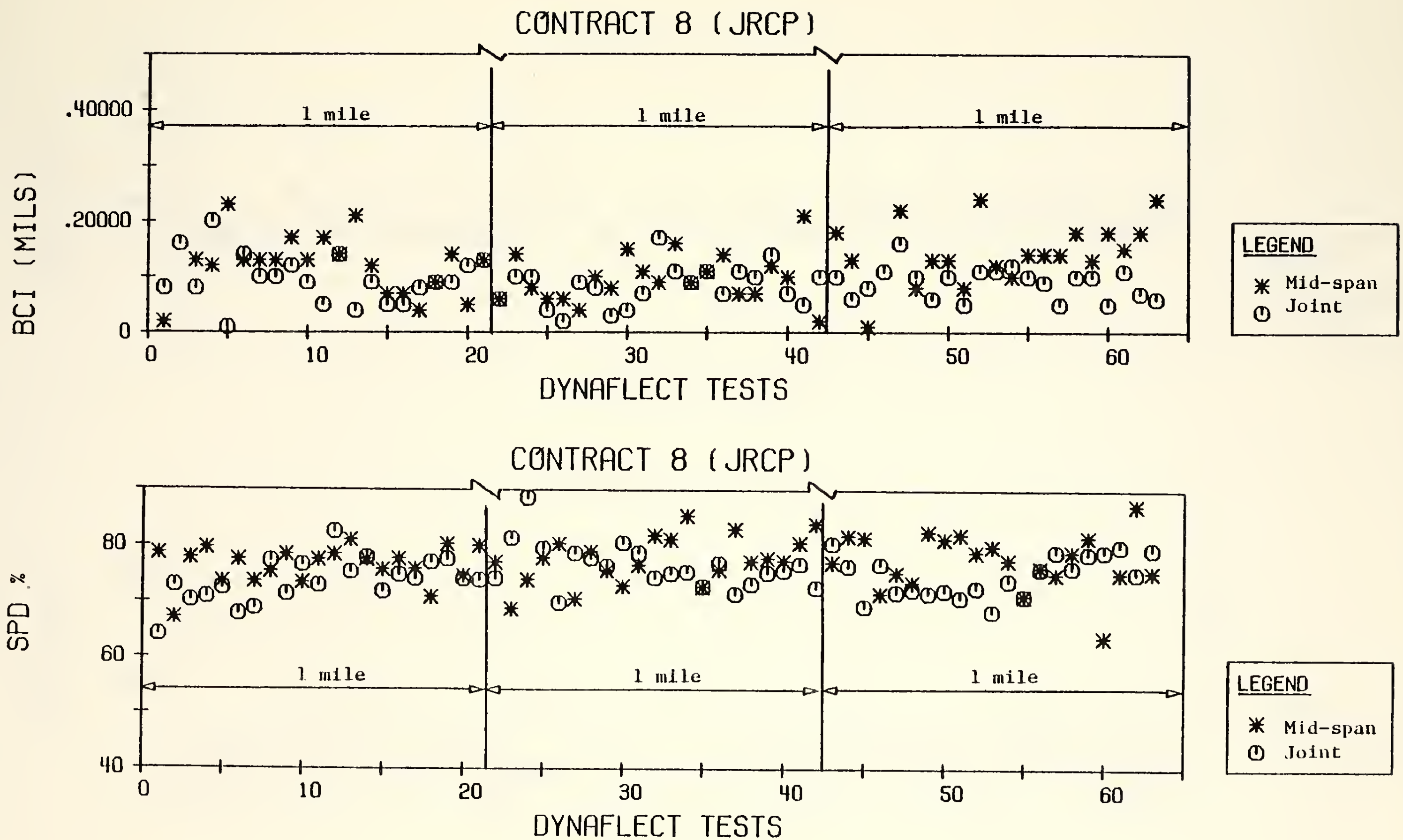

Figure G11. Variations of BCI and SPD Along Contract 8 (JRCP)

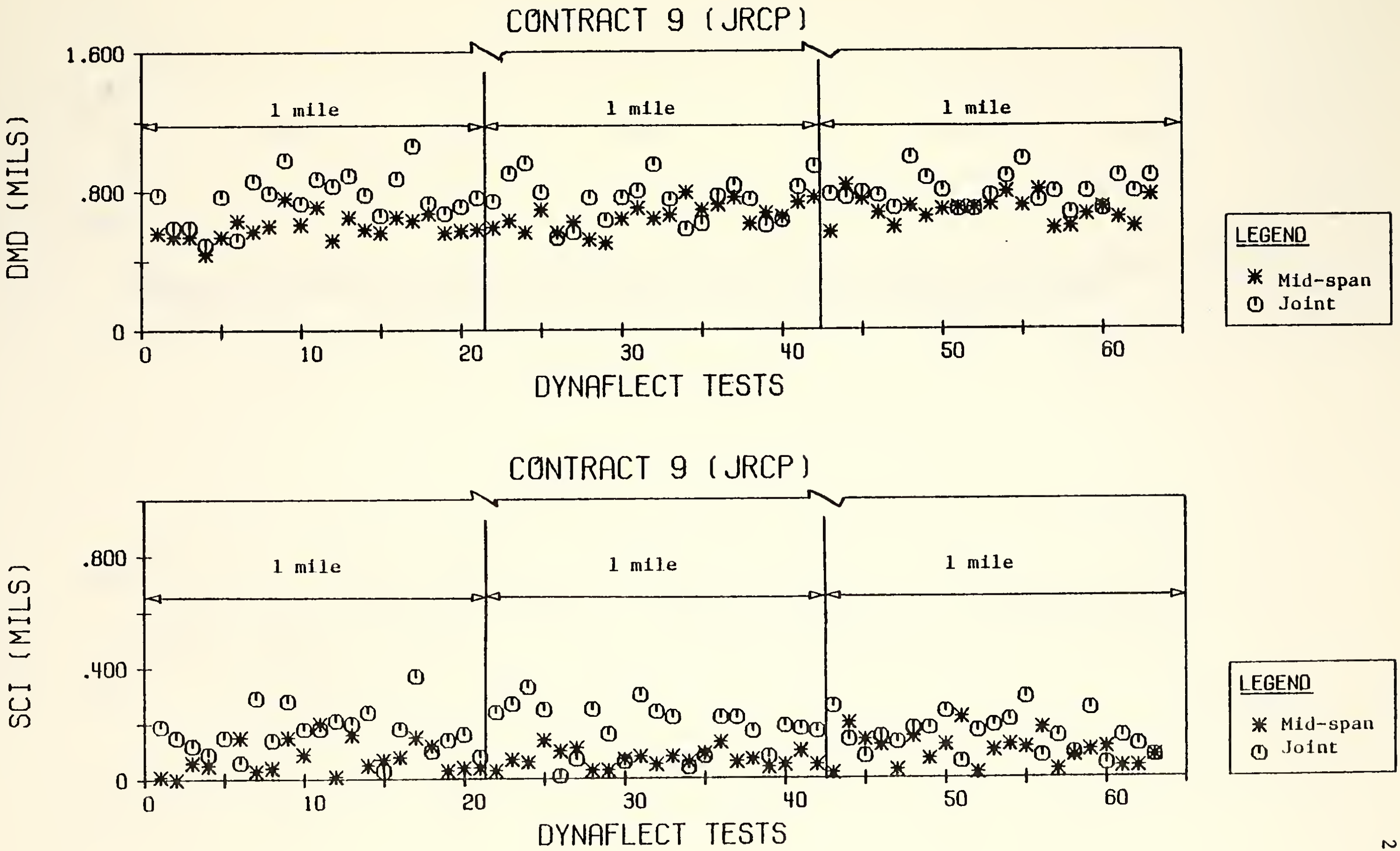

Figure G12. Variations of DMD and SCI Along Contract 9 (JRCP)

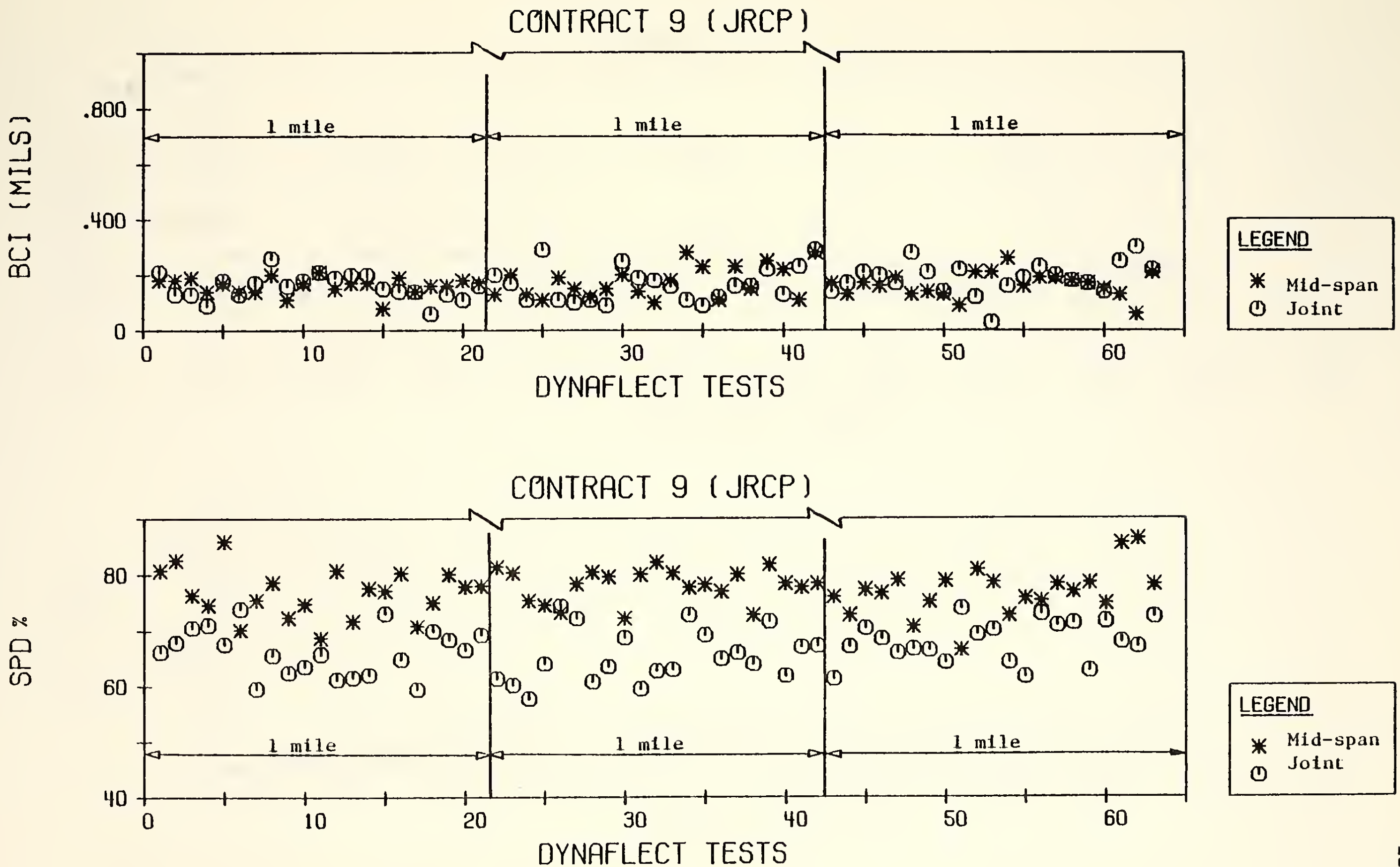

Figure G13. Variations of BCI and SPD Along Contract 9 (JRCP)

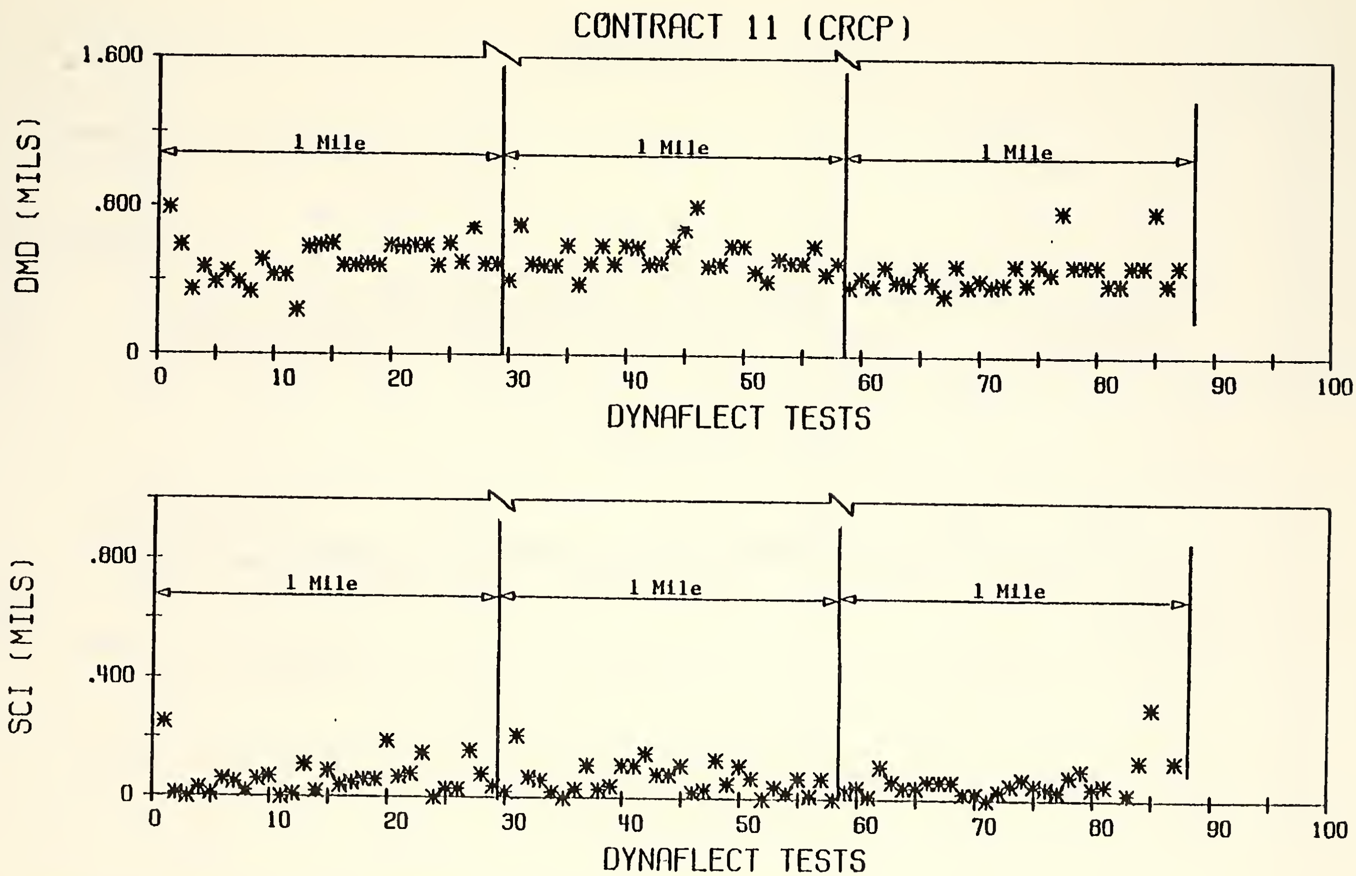

Figure G14. Variations of DMD and SCI Along Contract 11 (CRCP)

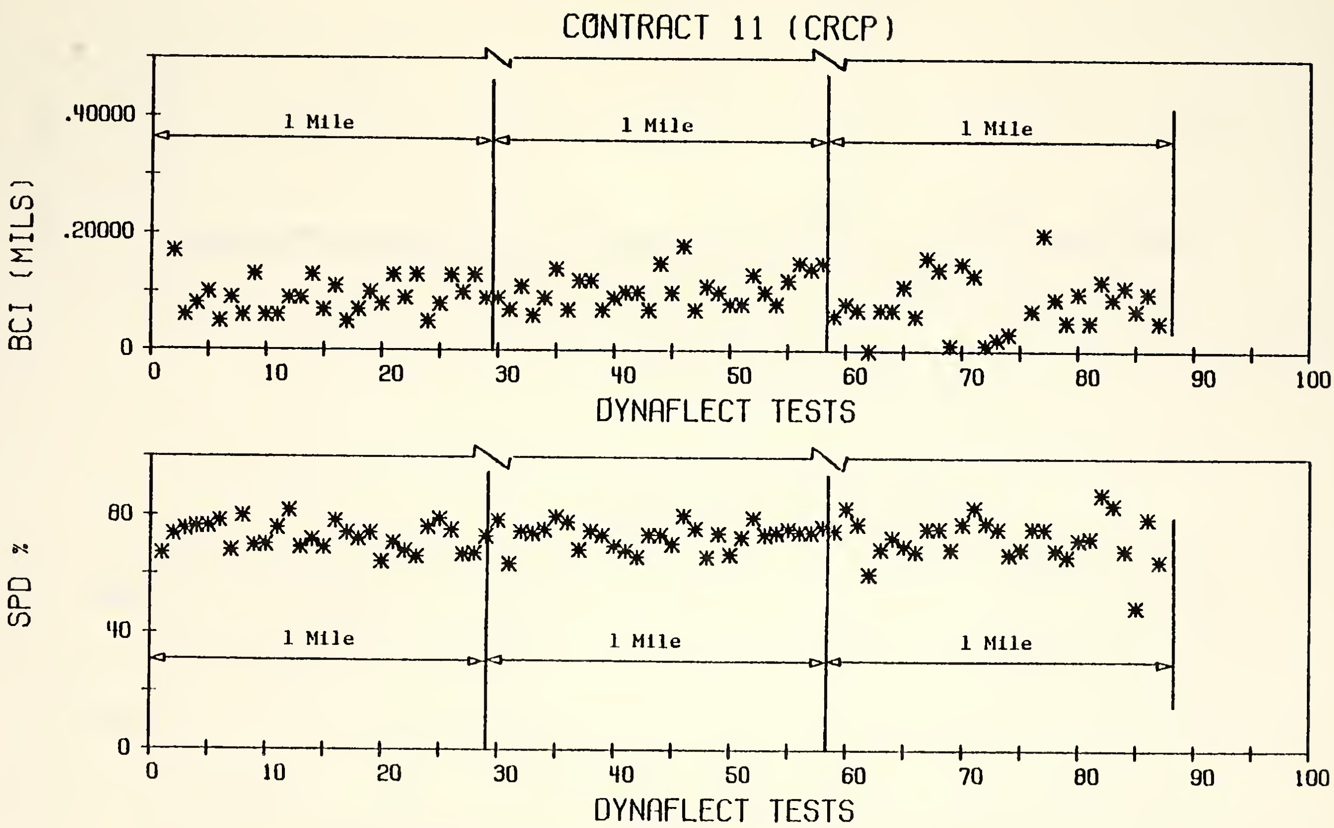

Figure C15. Variations of BCI and SPD Along Contract 11 (CRCP)

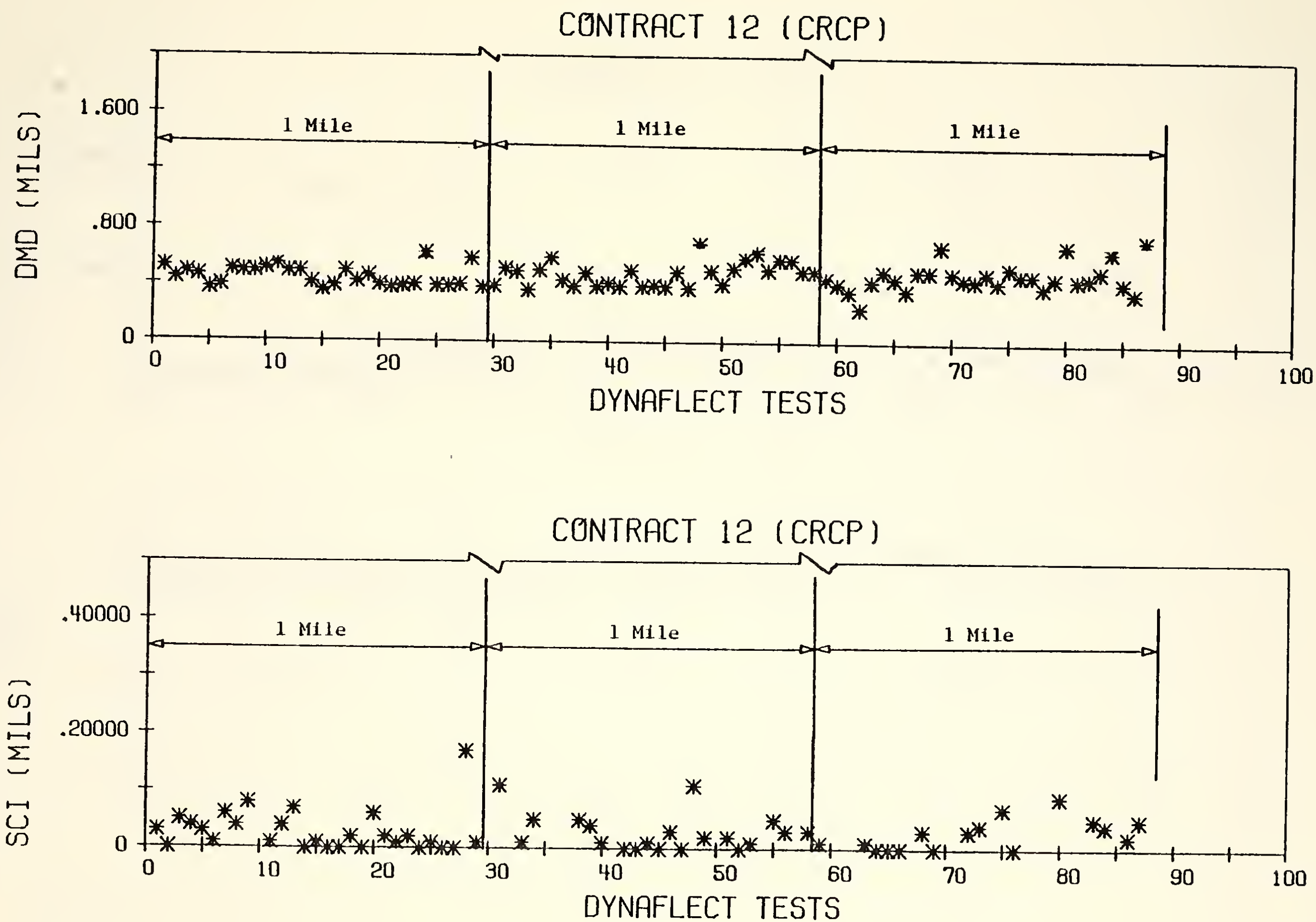

Figure G16. Variations of DMD and SCI Along Contract 12 (CRCP)

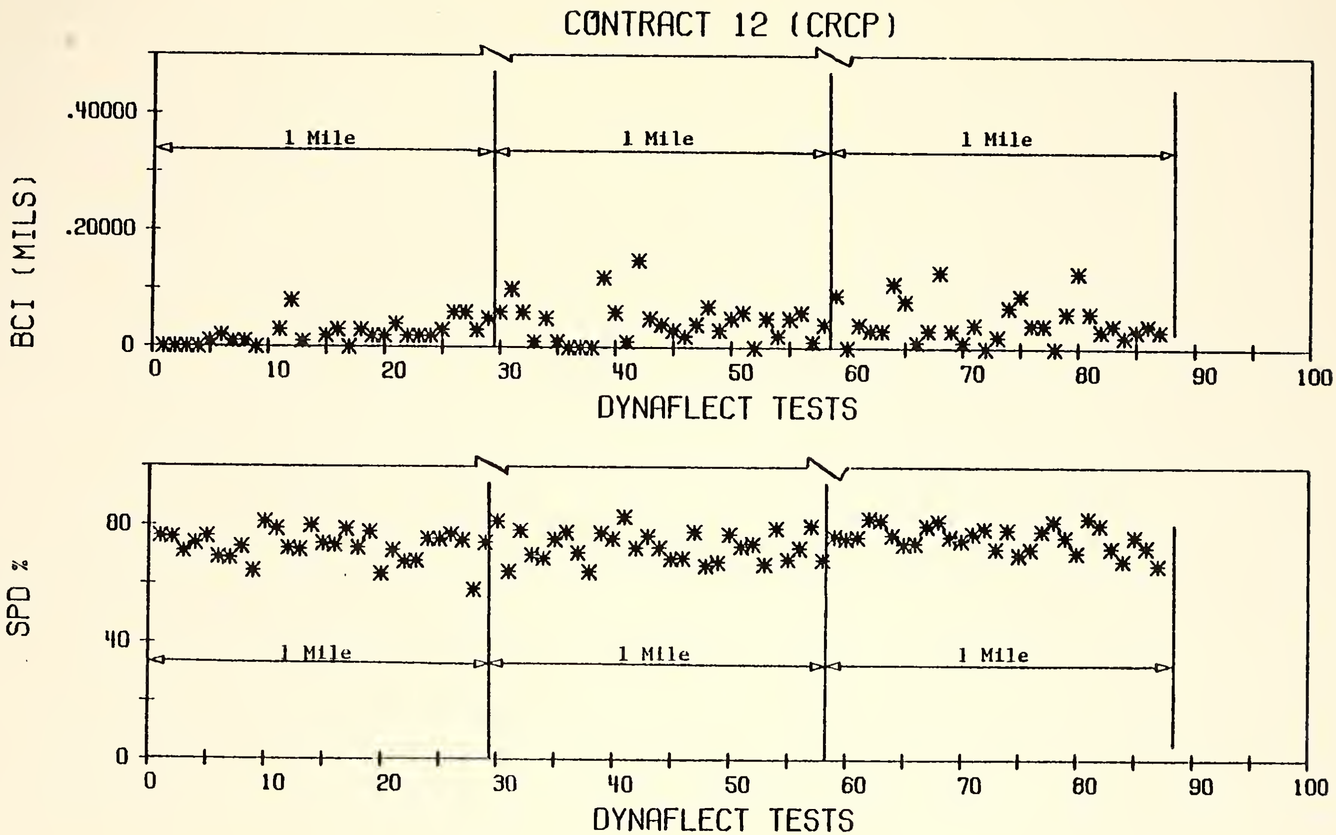

Figure G17. Variations of BCI and SPD Along Contract 12 (CRCP)

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